

The background features a series of overlapping circles in various shades of blue and teal. Within these circles, there is a silhouette of a city skyline, likely Vienna, with prominent domes and spires. The text is centered over this graphic.

# CAA 2026

31 march - 4 april

IT'S ALL ABOUT  
PEOPLE

*Vienna*

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ArcheoBase



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intraSiS  
intrasite information system



*heritage*

MAiA  
Managing  
Artificial Intelligence  
in Archaeology  
COST Action No. 23141

itml  
innovation applied

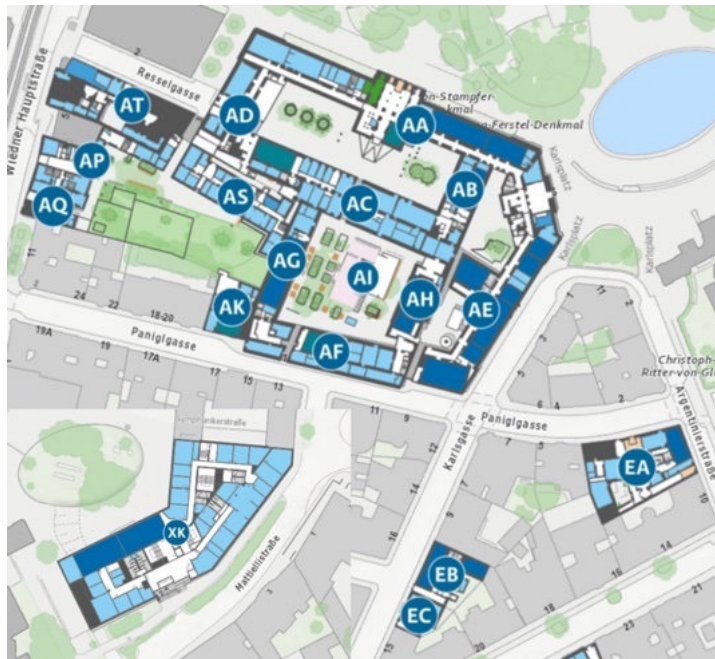
## Venues

### Workshops at TU Wien

On Tuesday 31 March 2026 CAA2026 will host a full day of workshops for participants.

They will take place at TU Wien (Vienna University of Technology).

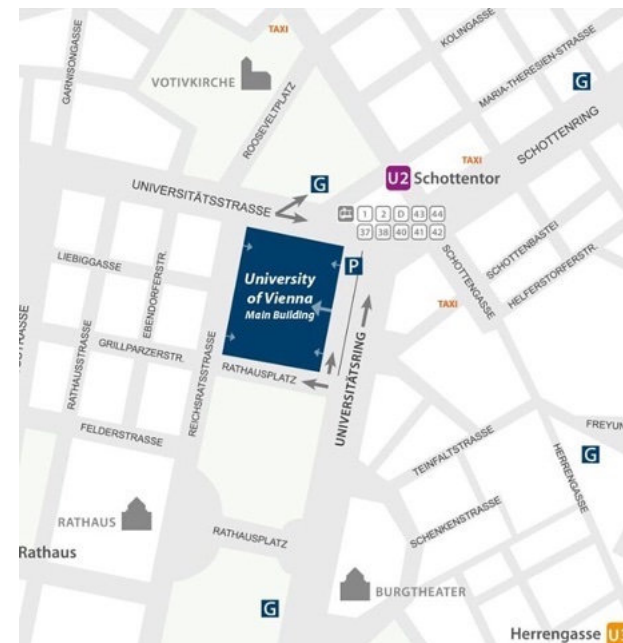
*TU Wien, Campus Karlsplatz: Karlsplatz 13, 1040 Vienna*



### Conference Sessions at University of Vienna

All sessions will take place 1 April – 3. April 2026 at the conference venue, University of Vienna, main building.

*University of Vienna: Universitätsring 1, 1010 Vienna*



# University of Vienna

## Lower Ground Floor (Tiefparterre): Lecture Rooms



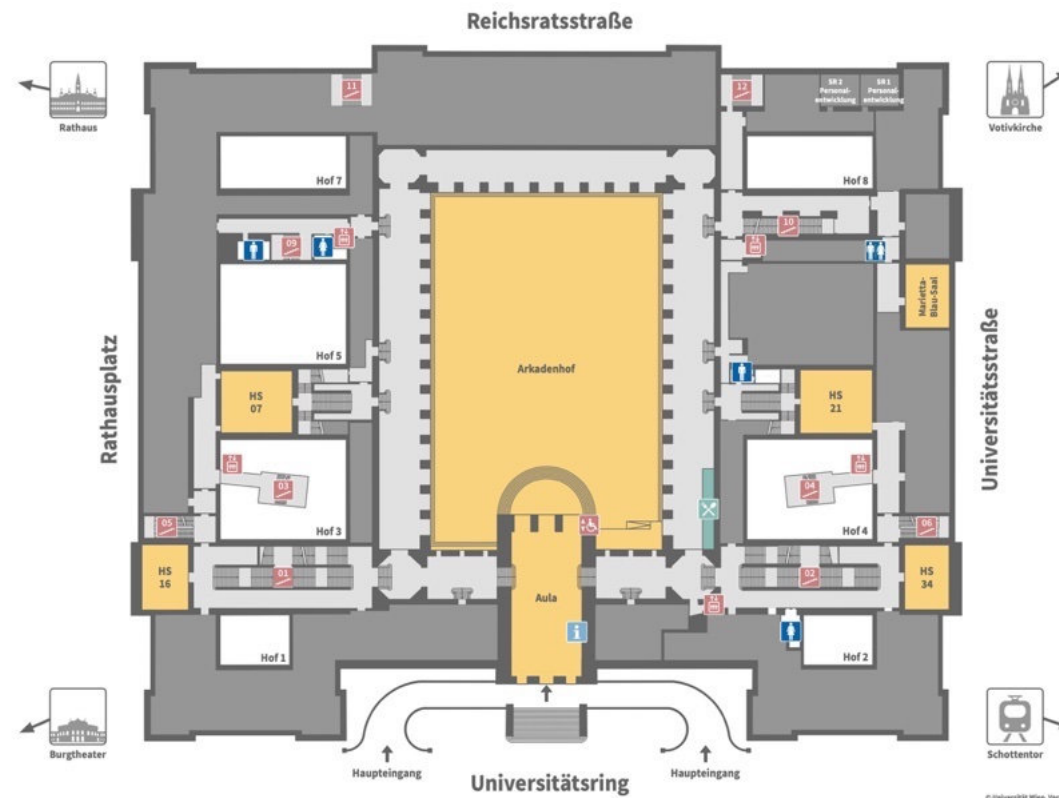
### Hauptgebäude der Universität Wien Tiefparterre Übersichtsplan



## Mezzanine Floor (Hochparterre): Registration and Information Desk



### Hauptgebäude der Universität Wien Hochparterre Übersichtsplan

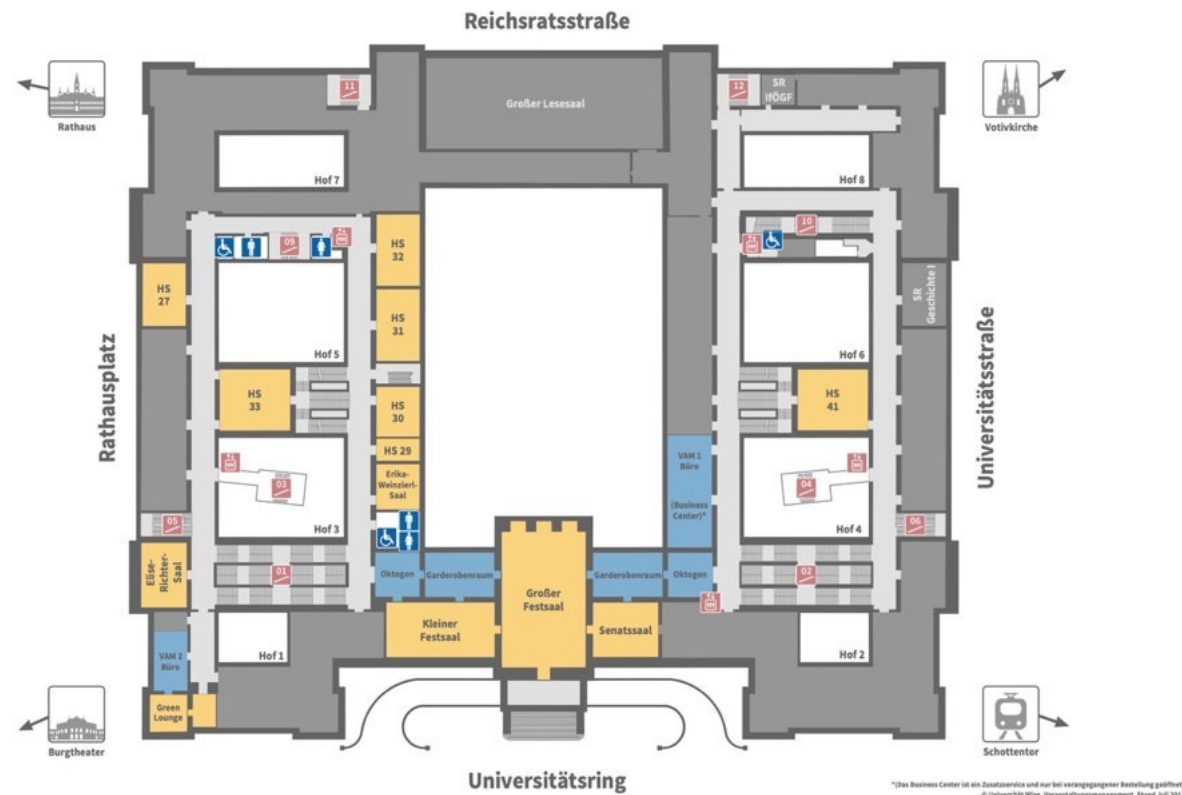


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## First Floor (1. Stock): Coffee Breaks, Poster Exhibition, Exhibition



### Hauptgebäude der Universität Wien 1. Obergeschoß Übersichtsplan



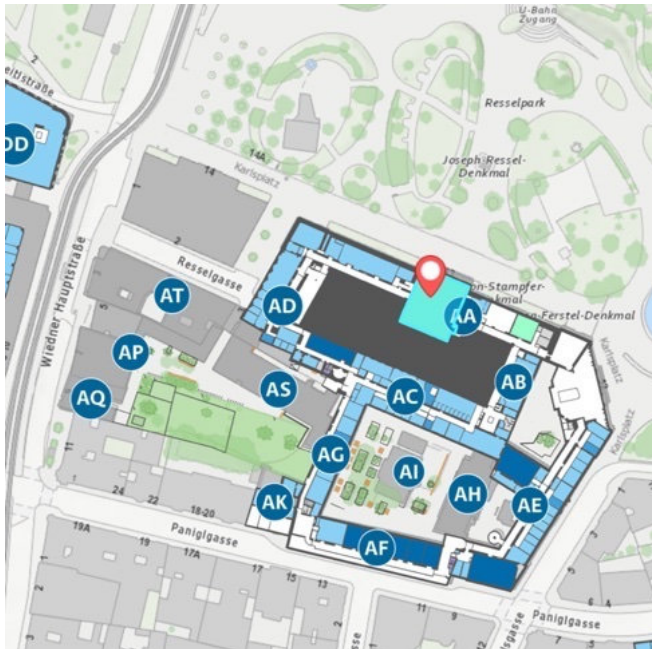


## Social Events

### Icebreaker Reception

The traditional CAA Icebreaker Reception is included in the conference fee and will take place in the Kuppelsaal at TU Wien on 31 March 2026 from 17:00 – 22:00.

*TU Wien, Campus Karlsplatz: Karlsplatz 13, 4th floor, 1040 Vienna*  
<https://maps.tuwien.ac.at/?q=AA0448>



### Conference Dinner

The CAA Conference Dinner will be held at *Heuriger 10er Marie* on 2 April 2026 from 19:00– 00:00.

Offered are typical Viennese dishes (meat, vegetarian, vegan), desserts and Viennese wine and *Most* (alcohol-free grape juice).

There is a limited number of places available, so make sure to book your ticket at registration!

*Heuriger 10er Marie* is 15 min away from the venue.  
Take tram 44 from Schottentor (direction Maroltingergasse) get off at Johannes Krawarik Gasse.

*Heuriger 10er Marie, Ottakringer Str. 222/224, 1160 Vienn*

# Schedule

| Tuesday, March 31 |                                                                    |                                                                                                                      |                                                    |                                                                              |                                     |                                                                                                                                                     |                                                                                                                  |                                                                          |                                                                                                               |                                                                           |
|-------------------|--------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------|------------------------------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| 09:00-12:00       | Exploring prehistory with the ROCEEH Out of Africa Database (ROAD) | Documenting Archaeological Fieldwork with iDAL.field: Hands-On Workshop on Usage, Configuration, and Synchronization | 3D documentation and multi-sensor data integration | Increasing interoperability and reproducibility of archaeometric data with R | From Zero to Plotting: R for Anyone | InSites: Gen-AI assistant for cultural significance assessment                                                                                      | Chronological modeling with ChronoLog: theory and practice                                                       | Itiner-e: contributing to the collaborative digital atlas of Roman roads | Using the ArchaMap application for data synthesis and FAIR data                                               | Open Hardware and Low-cost Electronics and IoT for sensing and monitoring |
| 12:00-13:30       | Lunch break                                                        |                                                                                                                      |                                                    |                                                                              |                                     |                                                                                                                                                     |                                                                                                                  |                                                                          |                                                                                                               |                                                                           |
| 13:30-16:30       | Exploring prehistory with the ROCEEH Out of Africa Database (ROAD) | Documenting Archaeological Fieldwork with iDAL.field: Hands-On Workshop on Usage, Configuration, and Synchronization | 3D documentation and multi-sensor data integration | Increasing interoperability and reproducibility of archaeometric data with R | From Zero to Plotting: R for Anyone | Seamless Visualization, Statistical Exploration, and Web Diffusion of Archaeological Spatial Data with the Open-source archeoViz Software Ecosystem | Publishing, Documenting and Enriching 3D Cultural Heritage Objects: A Hands-on Workshop with (Semantic) Kompakkt | Code review and best practices in programming                            | Efficient Archaeological Data Management with ArcheoBase: From Digital Data Entry to Analysis and Publication |                                                                           |
| 17:00-22:00       | Ice breaker party                                                  |                                                                                                                      |                                                    |                                                                              |                                     |                                                                                                                                                     |                                                                                                                  |                                                                          |                                                                                                               |                                                                           |

| Wednesday, April 1 |                                                                             |                                                                                                                                            |                                                                                                |                                                                                                                 |                                                                                                                                                      |                                                                                                 |                                                                                                       |                   |
|--------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|-------------------|
|                    | Auditorium Maximum                                                          | Hörsaal BIG                                                                                                                                | Franz König Saal                                                                               | Hörsaal 01                                                                                                      | Hörsaal 02                                                                                                                                           | Hörsaal 03                                                                                      | Hörsaal 05                                                                                            | Oktogon           |
| 08:30-10:00        | Welcome and Keynote                                                         |                                                                                                                                            |                                                                                                |                                                                                                                 |                                                                                                                                                      |                                                                                                 |                                                                                                       |                   |
| 10:00-10:30        | Coffee break                                                                |                                                                                                                                            |                                                                                                |                                                                                                                 |                                                                                                                                                      |                                                                                                 |                                                                                                       |                   |
| 10:30-12:30        | Session #3<br>Methodological and Theoretical Research in Digital Achaeology | Session #8<br>Digital Methods in Rock Art Research II. Connecting People: Reconstructing the Contexts of Past Visual Communication Systems | Session #49<br>Bridging Micro and Macro Perspectives in the Modelling of Past Human Ecosystems | Session #31<br>Computational Archaeology Revisited: Building Bridges with Mathematics and Computer Science      | Session #18<br>Connecting the Americas: A Pan-Regional Dialogue among CAA Chapters                                                                   | Session #47<br>Artificial Intelligence, a Step into the Post-digital Era of Archaeology?        | Session #5<br>People from the Underground: Towards a Digital Archaeology of Subterranean Environments | Poster session    |
| 12:30-13:30        | Lunch break                                                                 |                                                                                                                                            |                                                                                                |                                                                                                                 |                                                                                                                                                      |                                                                                                 |                                                                                                       |                   |
| 13:30-15:30        | Session #3<br>Methodological and Theoretical Research in Digital Achaeology | Session #8<br>Part II                                                                                                                      | Session #49<br>Part II                                                                         | Session #31<br>Part II<br>Session #36<br>Composed for Success: Making the Most of Chemical Data in Archaeometry | Session #30<br>Unstoppable Vision, Immovable Practice: An Adversarial Debate on Linked Open Dreams and the Reality of Archaeological Data Collection | Session #47<br>Part II<br>Session #20<br>Digital Archaeological Collections as AI Training Data | Session #5<br>Part II<br>Session #4<br>Computer Applications in South Asian Archaeology               |                   |
| 15:30-16:00        | Coffee break                                                                |                                                                                                                                            |                                                                                                |                                                                                                                 |                                                                                                                                                      |                                                                                                 |                                                                                                       |                   |
| 16:00-19:30        | Session #3<br>Methodological and Theoretical Research in Digital Achaeology | Session #8<br>Part III                                                                                                                     | Session #2<br>Our Little Minions VII: Small Tools with Major Impact                            | Session #36<br>Part II                                                                                          | Session #6<br>Unlocking Hidden Treasures: Digital Methods as the Key to Open Archaeological Collections for Research and Teaching                    | Session #20<br>Part II                                                                          | Session #4<br>Part II                                                                                 | Poster exhibition |

**8:00-18:00 - Registration and information desk, Aula, University of Vienna, Universitätsring 1, 1010 Vienna**

| Thursday, April 2 |                                                                                    |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |
|-------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|
|                   | Auditorium<br>Maximum                                                              | Hörsaal BIG                                                                                              | Franz König Saal                                                                                                                         | Hörsaal 01                                                                                                                                                 | Hörsaal 02                                                                                                            | Hörsaal 03                                                                                                              | Hörsaal 05                                                                                                    | Oktogon              |
| 8:30-10:30        | Session #3<br>Methodological and<br>Theoretical Research<br>in Digital Archaeology | Session #22<br>Ethics in Digital and<br>Computational<br>Archaeology                                     | Round Table #41<br>New Advances and<br>Directions of 3D<br>Analysis<br>in Archaeology                                                    | Session #1<br>Hic sunt dracones?<br>Link 'em all! Linked<br>Open Data, Wikidata<br>and CIDOC CRM in<br>Archaeology                                         | Round Table #24<br>Real-World<br>Perspectives on<br>Building Research<br>Data Infrastructures                         | Session #29<br>AI Across the<br>Heritage Pipeline:<br>From Algorithms<br>through Fieldwork to<br>Deliverables           | Session #16<br>"All Models are Wrong":<br>Learning from Failure<br>in Computational<br>Archaeology            | Poster<br>exhibition |
| 10:30-11:00       | Coffee break                                                                       |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |
| 11:00-13:00       | Session #3<br>Methodological and<br>Theoretical Research<br>in Digital Archaeology | Session #52<br>Beyond Fun and<br>Games?<br>Rethinking<br>Archaeogaming,<br>Play, and Digital<br>Heritage | Session #21<br>Computational<br>Approaches to<br>Archaeology in Latin<br>America and the<br>Caribbean:<br>Building Regional<br>Dialogues | Session #1<br>Part II                                                                                                                                      | Session #15<br>MuVAMoLa Part Two:<br>Multivariate Approaches<br>to Mortuary Landscapes                                | Session #29<br>Part II                                                                                                  | Session #14<br>Fighting Crime with<br>Computational<br>Archaeology                                            |                      |
|                   |                                                                                    |                                                                                                          |                                                                                                                                          | Session #19<br>Structuring the World<br>Beyond: Analytical and<br>Computational<br>Approaches towards<br>Protohistoric and Early<br>Medieval Funerary Data |                                                                                                                       |                                                                                                                         | Session #51<br>From Satellite to<br>Unmanned Platforms                                                        |                      |
| 13:00-14:00       | Lunch break                                                                        |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |
| 14:00-16:30       | Session #3<br>Methodological and<br>Theoretical Research<br>in Digital Archaeology | Session #52<br>Part II                                                                                   | Session #21<br>Part II                                                                                                                   | Session #19<br>Part II                                                                                                                                     | Session #17<br>Channels of Change<br>Interdisciplinary<br>Approaches to the<br>Archaeology of<br>Fluvial Environments | Session #42<br>The Reuse of Digital<br>Archaeological Archives<br>and Data: Pathway to<br>New Knowledge or<br>Dead End? | Round Table #35<br>Chronological Modelling<br>III<br>A Round Table on<br>Time in Computational<br>Archaeology |                      |
| 16:30-17:00       | Coffee break                                                                       |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |
| 17:00-18:30       | CAA International<br>AGM                                                           |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |
| 19:00-23:00       | Conference Dinner                                                                  |                                                                                                          |                                                                                                                                          |                                                                                                                                                            |                                                                                                                       |                                                                                                                         |                                                                                                               |                      |

**8:00-18:00 - Registration and information desk, Aula, University of Vienna, Universitätsring 1, 1010 Vienna**



| Friday, April 3 |                                                                                                                |                                                                                                                      |                                                                                                              |                                                                                                                                                                              |                                                                                                                                              |                                                                                                              |                                                                                                                                                        |                   |  |
|-----------------|----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|--|
|                 | Auditorium Maximum                                                                                             | Hörsaal BIG                                                                                                          | Franz König Saal                                                                                             | Hörsaal 01                                                                                                                                                                   | Hörsaal 02                                                                                                                                   | Hörsaal 03                                                                                                   | Hörsaal 05                                                                                                                                             | Oktagon           |  |
| 8:30-10:30      | Session #45<br>Computational Archaeology<br>at Scale: Large Spatial Datasets for Unveiling Cultural Landscapes | Session #25<br>How to do ROAD: An Essential Tool for Conducting Multidisciplinary Studies Related to Human Evolution | Session #43<br>Digital Evolution in Archaeological Practice: From Innovation to Infrastructure and FAIR data | Session #37<br>Future Sight on Past Landscapes: Vision Foundation Models for Archeological Remote Sensing and Landscape Archaeology                                          | Session #33<br>Generative AI, Text Mining, and Semantic Modelling: Using Big Models for Big Problems, FAIRly!                                | Session #40<br>Digital Archaeology for Heritage under Threat: Modelling Climate Hazards and Landscape Change | Session #44<br>Data are People: Data Making as Mirror of Past and Present Practice<br>Session #46<br>The Human Factor in Archaeological Data Recording | Poster exhibition |  |
| 10:30-11:00     | Coffee break                                                                                                   |                                                                                                                      |                                                                                                              |                                                                                                                                                                              |                                                                                                                                              |                                                                                                              |                                                                                                                                                        |                   |  |
| 11:00-13:00     | Session #45<br>Part II                                                                                         | Session #25<br>Part II<br>Session #32<br>Replay: Computational Heritage of Games                                     | Session #43<br>Part II                                                                                       | Session #50<br>Heritage under Bombs. Mitigating Destruction in Rapidly Evolving World                                                                                        | Session #33<br>Part II                                                                                                                       | Session #40<br>Part II<br>Session #12<br>Data Management Plans in Practice                                   | Session #46<br>Part II<br>Session #7<br>Reframing the Past: Cognitive, Psychological, and Computational Approaches to Interpreting Artefact Function   |                   |  |
| 13:00-14:00     | Lunch break                                                                                                    |                                                                                                                      |                                                                                                              |                                                                                                                                                                              |                                                                                                                                              |                                                                                                              |                                                                                                                                                        |                   |  |
| 14:00-16:00     | Session #9<br>AI Applications in Cultural Heritage and Archaeological Protection                               | Session #34<br>Modelling Seafaring: Methodological Retrospective and Future Roadmap                                  | Session #10<br>Exploring Past Senses. Digital Tools and Methodologies for Sensory Archaeology                | Session #50<br>Part II                                                                                                                                                       | Session #33<br>Part III<br>Session #27<br>Digital Communities: Collaborative Archaeologies, Shared Authority, and Community-Led Technologies | Session #39<br>Palaeo-GIS                                                                                    | Session #13<br>If I Had a Hammer, I'd 3D-Scan It: Computational Approaches for the Analysis of Tool Artifacts                                          |                   |  |
| 16:00-16:30     | Coffee break                                                                                                   |                                                                                                                      |                                                                                                              |                                                                                                                                                                              |                                                                                                                                              |                                                                                                              |                                                                                                                                                        |                   |  |
| 16:30-18:30     | Session #9<br>Part II                                                                                          | Session #34<br>Part II                                                                                               | Session #10<br>Part II                                                                                       | Session #11<br>Reframing Cultural Properties Rather than as "Relics of the Past" but as "Objects that Stimulate Modern People's Perception, Sensibility, and Meaning-Making" | Session #27<br>Part II                                                                                                                       | Session #39<br>Part II                                                                                       | Session #13<br>Part II                                                                                                                                 |                   |  |

8:00-17:00 - Registration and information desk, Aula, University of Vienna, Universitätsring 1, 1010 Vienna



## Tuesday

### Full-day workshops

#### Exploring prehistory with the ROCEEH Out of Africa Database (ROAD)

*Christian Sommer, ROCEEH Research Center*

*Jesper Borre Pedersen, ROCEEH Research Center*

*Christine Hertler, ROCEEH Research Center*

*Andrew Kandel, ROCEEH Research Center*

ROCEEH Out of Africa Database (ROAD) is a comprehensive, interdisciplinary resource for the study of human evolution (Kandel et al. 2023). Developed over the past 18 years by the ROCEEH research center (The Role of Culture in Early Expansions of Humans), ROAD integrates archaeological, anthropological, and paleoenvironmental data from Africa and Eurasia, spanning a period from 3,000,000 to 20,000 years before present.

ROAD currently contains information on over **28,000 assemblages** and **2,600 localities**, compiled from more than **6,300 publications in over 10 languages**.

It has become a critical tool for researchers conducting quantitative, computer-based analyses of human evolutionary history at multiple spatial and temporal scales (see:

<https://www.zotero.org/groups/5497463/roceeh/library>).

This **full-day workshop** offers an introduction to the structure and core concepts behind ROAD. Participants will engage in **hands-on exercises** using browser-based user interfaces for streamlined data exploration. The workshop will also introduce the newly developed **R package ‘roadDB’**, which enables seamless access to ROAD through one of the most widely used platforms for data analysis.

Finally, participants will have the opportunity to develop and run their own queries, with direct support from the ROCEEH team, playing the groundwork for incorporating ROAD into their own research.

#### References:

<https://www.roceeh.uni-tuebingen.de/roadweb/>

Kandel, A. W., Sommer, C., Kanaeva, Z., Bolus, M., Bruch, A. A., Groth, C., Haidle, M. N., Hertler, C., Heß, J., Malina, M., Märker, M., Hochschild, V., Mosbrugger, V., Schrenk, F., Conard, N. J. (2023). The ROCEEH Out of Africa Database (ROAD): A large-scale research database serves as an indispensable tool for human evolutionary studies. PLOS ONE, 18 (8), e0289513.

<https://doi.org/10.1371/journal.pone.0289513>

# Documenting Archaeological Fieldwork with iDAI.field: Hands-On Workshop on Usage, Configuration, and Synchronization

*Fabian Riebschläger, German Archaeological Institute*

*Lisa Steinmann, German Archaeological Institute*

iDAI.field (<https://github.com/dainst/idai-fieldn>) is free, open-source software for documenting archaeological fieldwork. It was developed and used by the German Archaeological Institute (<https://www.dainst.org/>) since 2016, and has since 2023 been further advanced in the context of NFDI4Objects in collaboration with VZG (<https://www.gbv.de/informationen/Verbundzentrale/>).

The iDAI.field ecosystem comprises FieldDesktop (offline-first data capture), Field Hub (internet synchronization), and Field Web (publication), enabling an end-to-end workflow from trench to dissemination. Its configurable data model, validation features, and open, standardized exchange formats support re-usability, comparability, and downstream archiving in line with FAIR principles.

## Core capabilities

- A core data model for archaeological excavations that ensures basic comparability of all projects created with iDAI.field
- Flexibility to extend this data model, so that it can be adapted to the needs of different archaeological domains via a graphical configuration management. Built-in mechanisms for standardization and quality management to support comparability and reuse.
- Integrated image handling and geodata support.
- A customizable type management for e.g. find classification.
- A multilingual user interface (currently translations in 7 languages available) and multilingual data entry in any language .

- Inventory support with QR-code recognition.
- Full offline functionality with robust synchronization, both offline and online.
- Installation on all common desktop operating systems
- Strong emphasis on easy usability for quick on-boarding of field personell, such as students
- Import and export in standardized, open file formats
- Data and configuration access via REST API for integration with other systems or data analysis

## What the workshop covers

This hands-on session introduces the essentials for using and tailoring iDAI.field with curated sample data. Short inputs alternate with practical exercises to help participants:

- Set up a project; understand the core data model, entities, relations, value lists, and type management.
- Configure an extended data model via graphical tools for different usage scenarios.
- Manage images and integrate geodata effectively.
- Apply quality-assurance and standardization options that enhance comparability and reuse.
- Import and export data with open formats.
- Collaborate safely using local backups and synchronization across multiple desktops
- Explore the REST API for lightweight interoperability with external systems

The workshop is designed to be directly transferable to active or planned field work without requiring programming skills

Target audience: Researchers at all career stages working in excavation, building archaeology, find processing or on surveys, who want offline, robust, shareable, and maintainable digital field documentation workflows.



## 3D documentation and multi-sensor data integration

*Ing. Bernhard Groiss, RIEGL LMS GmbH*

*Dr. Matthias Kucera, RIEGL LMS GmbH, University of Vienna*

3D recording techniques became manifold during the last two decades, when laserscanning was first being used for archaeological purposes. Early work started to deal with terrestrial Laserscanning (TLS) for recording architecture, archaeological excavations and archaeological landscapes. Airborne Laserscanning (ALS) is also applied for detecting new archaeological structures under vegetation cover. In addition, photogrammetric methods (Image based Modelling) became a complementary tool, which is used widely. To guarantee comparability of datasets standardized workflows for data acquisition, processing and filtering are crucial.

It is a great honour for Riegl LMS to organize a workshop aiming on the application of Laserscanning in cultural heritage and archaeological research. Long-term expertise in survey planning, processing, filtering, analysis and presentation of the data will be brought in by our trainers and partners. It is also a chance for us to learn more about current specific demands of archaeological research for more accurate implementation of features to our products. In this sense we are pleased to share our knowledge to pin down standardized methods for 3D recording of archaeological entities.

In the **first part** of the proposed workshop, we want to focus on TLS consisting of:

- Survey strategies
- Georeferencing including coordinate systems
- Monitoring
- Processing workflows
- Combination of TLS data and 3rd party results in RiSCAN PRO, Filtering of vegetation (LIS TreeAnalyzer, RiSCAN PRO plug in) and other filtering techniques

- Preparation of data for display and presentation
- Exchange with GIS-tools and software
- Practical training will be carried out with Riegl LMS VZ-600i and the software RiSCAN PRO

In **part two** complementary datasets and their integration will be presented:

- Unmanned Aerial Laser scanning (ULS)
- survey strategies
- data processing and filtering
- Combination of TLS and ULS (ALS) datasets
- Bathymetric Laserscanning (BLS)
- technical introduction
- overview of the integration of photogrammetric datasets (Image based Modelling, Reality Capture)
- Integration of other sensor data (Infrared)
- Interface to GIS-software

**Attendees will benefit from:**

- Presentation of newest TLS, ULS and BLS Laserscanners from Riegl LMS
- Practical training with VZ-600i
- Integration of different datasets (TLS, ULS, BLS)
- Basic knowledge of the software RiSCAN PRO
- Design of specific survey strategies
- Presentation of results
- Analysis of the data
- Preparation of data for further spatio-temporal analysis in GIS and other tools

## Increasing interoperability and reproducibility of archaeometric data with R

*Thomas Rose, Leibniz-Forschungsmuseum für Georessourcen/Deutsches Bergbau-Museum Bochum*

*Alexandra Rodler-Rörbo, Austrian Archaeological Institute, Austrian Academy of Sciences*

Increasing interoperability of datasets is pivotal for the implementation of the Open Science principles throughout the research data life cycle. As a step forward in archaeometry (the material-scientific analysis of usually inorganic archaeological materials) towards this goal, (<https://www.lorentzcenter.nl/towards-an-archaeological-science-toolbox-in-r-astr.html>) a workshop at the Lorentz Center in Leiden developed a common language for naming of datasets and data conventions in October 2025. The results were formalised in the R package ASTR (<https://github.com/archaeo-thommy/ASTR>) and are described in its vignettes.

In addition to this common language, ASTR includes a collection of commonly used tools for data processing, visualisation, and interpretation in archaeometry to ease the transition from Excel and similar software towards scripting languages, increasing reproducibility and transparency. In this regard, ASTR is envisioned to complement existing and future packages for other specialisations in the archaeological sciences, ultimately creating an interoperable software ecosystem for the archaeological sciences and neighbouring fields.

This hackathon aims to continue the work started at the Lorentz Center while opening the project to the entire community. During the hackathon, the participants will be introduced to the common language and will be trained on how to integrate it in their functions. The workshop will focus on the development and refinements of the common language and participants can

either work on functions and tools for ASTR or on adding support for the common language in other packages.

In addition, the workshop will offer the opportunity to meet the maintainers of ASTR and to discuss with them. ASTR is envisioned to be developed in a community effort, meaning that the maintainer team welcomes anyone who wants to join them on their quest towards interoperability and repeatability in archaeometry and beyond. Consequently, the next steps of the project will be discussed with all participants during the workshop.

## From Zero to Plotting: R for Anyone

*Petr Pajdla, Czech Academy of Sciences, Institute of Archaeology, Brno*

*Peter Tkáč, Czech Academy of Sciences, Institute of Botany*

*Vít Kozák, Masaryk University, Department of Archaeology and Museology*

### ***“We will close your brackets and find all your missing commas!”***

Intimidated by R? You're not alone. Whether you've never written a line of code or struggled through previous attempts, this workshop is designed for you. We'll demystify R and show you that data analysis and visualization aren't just possible for archaeologists, they're powerful tools that will transform how you work.

Over this hands-on session, we'll guide you through the complete workflow: installing essential packages, reading, transforming and plotting data and ultimately understanding why R matters for reproducible research. We'll use archaeological data, clean it up, organize it the “tidy” way, transform it to answer your questions, and create publication-ready plots.

We want you to leave the workshop with confidence to keep on coding!

### **What You'll Learn**

- Starting R and R Studio for the first time
- Installing packages

- Working in scripts and projects
- Reading your data with readr package
- Data cleaning and organizing them the *tidy* way with tidyr package
- Transforming and summarizing data with dplyr package
- Creating compelling visualizations in ggplot2 package

#### Who Should Apply

- Complete beginners with no coding experience
- People who've tried R before and found it frustrating
- Archaeologists wanting to improve data analysis and visualization skills
- Anyone curious about reproducible research workflows
- No prior programming experience necessary
- Just bring your laptop (with R (<https://cran.rstudio.com/>) and RStudio (<https://posit.co/download/rstudio-desktop/>) installed) and willingness to learn.

**Format:** Hands-on coding workshop with guided examples, archaeological datasets, and time to practice. We'll troubleshoot together and emphasize learning over perfection

This workshop is co-organized by **CAA Special Interest Group on Scientific Scripting Languages in Archaeology (SSLA)**, see <https://sslarch.github.io/>, (<https://sslarch.github.io/>)

## Half-day workshops

### Open Hardware and Low-cost Electronics and IoT for sensing and monitoring heritage assets

*Juan Palomeque-Gonzalez, IDEA, Madrid*

The rapid development of sensing technologies and analytical methods has made the use of IoT and smart devices increasingly valuable for monitoring environmental conditions that affect heritage assets, such as museum collections, archaeological sites, and historic buildings. Yet, the high cost of many commercial solutions often creates barriers for research teams with limited budgets. Furthermore, even affordable devices are frequently tied to proprietary service providers and closed cloud platforms, restricting flexibility and long-term sustainability.

This workshop introduces participants to open hardware and low-cost electronics for designing and building customised monitoring systems. We will begin by exploring Microcontroller Units (MCUs), the core of IoT sensing devices, including widely used models such as the Raspberry Pi Pico, ESP32, ESP8266, and Arduino. Their differences, capabilities, and coding approaches will be compared to help participants select the most suitable option for their projects.

We will then examine a range of commonly used sensors and interface components, such as temperature and humidity sensors, motion and distance detectors, light sensors, switches, LEDs, and small displays. While it is not possible to cover the full spectrum of devices, the workshop will provide practical examples and general principles that can be applied across many sensor types.

Coding fundamentals will be introduced using open-source tools and two key programming languages: MicroPython, a lightweight Python implementation for microcontrollers, and Arduino C, a C++ variant originally developed for

Arduino boards. Participants will learn how to connect sensors to MCUs, write simple programs, and build functioning prototypes.

In the final section, we will explore the networking capabilities of these devices, demonstrating how to gather, store, and analyse data locally or via open cloud-based solutions.

This will be a hands-on workshop, where attendees will not only gain theoretical knowledge but also actively construct and program simple IoT prototypes, leaving with both practical skills and a foundation for developing their own heritage monitoring projects.

## Efficient Archaeological Data Management with ArcheoBase: From Digital Data Entry to Analysis and Publication

*Dr Emmanuel Clivaz, ArcheoBase*

*Jean-Philippe Clivaz, ArcheoBase*

The session will be led exclusively by the founders of ArcheoBase, who will present the ArcheoBase platform.

### Question Answered by this workshop

- How can we effectively overcome resource limitations (human, financial, and material) in archaeology to improve data collection and analysis?
- What are the best practices for developing and implementing standardized methods in archaeological data processing?
- How can we establish a unified, accessible online database to facilitate data sharing, knowledge transfer, and collaboration across institutions?

- How to enhance the accessibility of archaeological data and publications for both the public and researchers, ensuring cultural heritage preservation and visibility?

### Summary

Participants will engage in an end-to-end journey of archaeological data handling, from initial data entry during excavation, through post-excavation analysis, to final publication, addressing critical questions using ArcheoBase.

### Workshop Outline

Excavation and Data Entry:

Beginning in the field, participants will learn to record archaeological data efficiently using ArcheoBase, ArcheoEntry module, tailored for dynamic and adaptable data entry. This phase emphasizes the importance of capturing accurate data directly on-site, reducing redundancy, and minimizing errors that often arise from traditional paper-based methods. Through customizable digital forms, participants will capture data in a manner that is compatible with their own workflow and methodology, ensuring accuracy and consistency from the start. Participants will create digital forms based on their own paper templates, learn how to use the module to streamline teamwork on excavation sites, especially on large projects with multiple sectors and team members. They will experience live data entry directly from tablets or mobile devices, allowing everyone to capture information simultaneously and in real-time.

Post-Excavation Analysis:

Moving to the post-excavation phase, the workshop will delve into data management and analytical techniques facilitated by ArcheoBase. Participants will utilize tools for organizing, validating, and analyzing data, including the integration of GIS and photogrammetry. Participants will learn how to link diverse data types, such as photographs, drawings, and forms, to create a comprehensive, integrated dataset. Through hands-on exercises, participants will see how ArcheoBase capabilities support the automated

generation of Harris matrices enhancing the interpretative depth of the data collected. Participants will also get an exclusive preview of ArcheoBase, latest feature in development, a web-based, geolocalized drawing tool. This tool enables precise, GIS-integrated vector drawings directly in a browser. The participants will export their data in xlsx format for comprehensive backups and further work with other software (R, python, etc.). They will also use Web Feature Services (WFS) that allows a direct synchronization between ArcheoBase and spatial analysis/mapping tools such as QGIS.

#### Data Publication and Accessibility:

In the final phase, the workshop addresses the publication of archaeological data for both public access and academic use. Using ArcheoBase, ArcheoPublication and ArcheoView modules, participants will learn the process of preparing data for online publication, ensuring accessibility while safeguarding data integrity. ArcheoPublication also enables user to directly publish their work on their own institution, website via an IFrame, offering seamless integration and broader accessibility. This phase will highlight the platform, capacity to facilitate open data initiatives and public engagement, thus contributing to cultural heritage preservation.

Attendees will explore strategies to facilitate the handling of meta-projects, such as the swiss palafitte project, where members come from different institutions and collaborate on a centralized database for data entry and publication.

## Code review and best practices in programming

*Matteo Tomasini, University of Gothenburg, Sweden*

With the introduction of more and more digital tools in archaeology, most journals made it mandatory to publish software on a public repository such as Zenodo or Github, even when said software is not the central topic of a

paper. However, during the process of peer review after submitting a paper, only a few journals requires of their reviewers to review a software. Additionally, in many cases the review does not follow a specific protocol to ensure that the code is running and functional. In other words, ensuring the correctness of code review is up to the reviewer's time, capability and willingness.

On the contrary of code review performed in business software development settings – which aims at functionality as well as at uniforming a code base written by several individuals – the process of scientific code review aims at making sure that a code functions correctly, but it also aims at making it more readable by external individuals, and more usable in the future both as its own piece of software, or for further development. The consequence of lack of software review is that a lot of software becomes unavailable a few months after publication – either because it was not written nor assessed to ensure maintainability, or because the original developers left the building and nobody is able to pick up the obscure code.

A simple way to decrease the amount of published unusable software, is to perform code review on each piece of software that see the light of day on a journal. However, code review requires the collaboration of developers who are tasked with writing code better. This is why it is paramount to spread good practices in archaeological programming: these include code documentation (e.g. comments in the code), unit testing, proper software design and good stylistic writing. Learning these principles makes of us better software developers, but also contributes to making review of software easier on reviewers.

In this workshop, we will learn about software design principles and best practices in programming through a look at scientific code review. A short presentation will be followed by some hands-on work.

## Using the ArchaMap application for data synthesis and FAIR data

*Robert J. Bischoff, Arizona State University*

*Daniel J. Hruschka, Arizona State University*

This workshop introduces ArchaMap, an application and database belonging to the CatMapper project, that facilitates synthetic research in archaeology by mapping and merging datasets through a transparent, reproducible process. ArchaMap is designed to assist users in creating and storing translations of complex categories (e.g., sites, ceramic types, periods) across datasets. Users can integrate diverse categories such as ceramic types, projectile points, time periods, culture areas, sites, or any other type of archaeological category. ArchaMap aligns with FAIR principles (Findable, Accessible, Interoperable, Reusable), ensuring data is easy to manage, share, and reuse across projects.

As an example, the cyberSW database in the Southwest US contains data on millions of ceramic sherds mapped to distinct ceramic types. ArchaMap provides tools to (1) to help users link ceramic types from new projects to the cyberSW ceramic types for new analyses, and (2) publicly share those new linkages for others to re-use.

Specifically, if a user has a spreadsheet of ceramic types from a new project, they can use ArchaMap's translation tools to automatically find the best matches for existing ceramic types within the ArchaMap database leveraging a comprehensive set of alternate names and contextual information already included in the database. They can also limit their search to only those ceramic types currently used by the cyberSW database and those from a specific region or time period. These matches can then be verified for accuracy and modified as necessary. New categories can be created if a ceramic type does not currently exist within the database. After fully translating the new

project's ceramic types, the user can then upload the new project's metadata and the translations of its ceramic types to ArchaMap categories

After storing the new translation, several ArchaMap tools permit users to find and re-use these translations between their dataset and the cyberSW dataset for future work. This process can be repeated to link multiple datasets. As new datasets are uploaded, each new translation increases the pool of alternate names available for matching, thereby making matching easier in the future. ArchaMap provides tools for easily finding metadata (including Citation and location or url) on more than 2000 linked datasets, making their data more findable and accessible. By linking categories from one's dataset to an ArchaMap category with a permanent URL and unique CMID (CatMapperID), it makes one's data more findable and interoperable. By permanently storing the linkages between datasets, the data becomes more reusable

Another key aspect of ArchaMap is that it encodes multiple competing typologies. Researchers may choose to constrain matches by context or dataset to choose a particular typology that suits their needs or they can upload their own typology. The user is able to determine what constitutes a match and modify the translation to fit their needs. Disagreements in matches will be highlighted by the application and left for the user to moderate. This workshop is suitable for researchers at any stage, with any type of data, from any region.



## Itiner-e: contributing to the collaborative digital atlas of Roman roads

*Adam Pažout, Universitat Autònoma de Barcelona, Spain*

*Pau de Soto, Universitat Autònoma de Barcelona, Spain*

### Itiner-e

The digital atlas of ancient roads (<https://itiner-e.org>) is an open online platform where it is possible to view, query, and download Roman road data. The digital atlas is currently populated by a dataset of some 300,000 km of roads covering all of Roman Empire that is a result of a joint effort of projects Viator-e: The Roads of the Western Roman Empire (PI Pau de Soto) and MINERVA: Understanding the centuries-long functioning of the Roman economy (PI Tom Brughmans, lead data collection Adam Pažout) with contribution from other collaborators from European and non-European institutions. While the current dataset appears impressive, it is far from complete and perfect. Many regions are poorly covered while in others spatial resolution and accuracy of the road data is low. Itiner-e was from the start intended to be an open platform, a scientific repository for researchers to share their research on Roman roads and contribute to the living atlas so that Itiner-e can become a comprehensive database and research tool for scholars and students and a dissemination tool for the public.

The aim of this workshop is to introduce the participants to the key concepts and functions of the platform, its data structure and how new data can be added and edited. In the first part of the workshop, we focus on the interface of the online platform, how to view, query, select, and download the Roman road data. The second part of the workshop is dedicated to the data structure, how the data can be created, prepared, and uploaded to the database. This is illustrated on practical exercises and real-world data. Finally, we would like to discuss with the participants methodological considerations in ancient road digitization, data standards, open data and FAIR principles in

sharing research data on Itiner-e platform. With this workshop we hope to consolidate a growing community of scholars and students around Itiner-e so it can become living atlas of Roman roads showing the state-of-the-art of research on Roman road network. However, we would also like to invite researchers not working on Roman roads as we welcome insights from broader field of road archaeology and are ready to share and exchange our experiences from making Itiner-e.

## Publishing, Documenting and Enriching 3D Cultural Heritage Objects: A Hands-on Workshop with (Semantic) Kompakkt

*Zoe Schubert, TIB Leibniz Information Centre for Science and Technology and State Library Berlin*

*Maria Sotomayor, University of Cologne*

*Øyvind Eide, University of Cologne*

3D models are an essential component of archaeological and cultural heritage research, yet sustainable workflows for publishing, enriching, and documenting such data remain challenging. Researchers must navigate questions of interoperability, semantics, and annotation, and long-term accessibility while ensuring that their 3D data remain usable and citable in scholarly contexts. This half-day workshop introduces participants to open, standards-based methods for publishing and semantically enriching 3D cultural heritage objects, using the open-source platform Kompakkt as a central tool.

Kompakkt, originally developed at the University of Cologne, is an open-source infrastructure designed specifically for scholarly use and flexible presentation of 3D models. It supports viewing, annotating, and sharing 3D objects in a web-based environment. The platform also integrates with established cultural heritage data standards (e.g., the new IIIF 3D standard) and

allows embedding in digital research environments. Its semantic extension, developed within the NFDI4Culture (<https://nfdi4culture.de/>) consortium at TIB in Hannover, provides an optional layer for linking 3D content with semantic web technologies, enabling persistent identifiers, interoperability, and machine-readable documentation. Together, these components exemplify how 3D data can be made FAIR (Findable, Accessible, Interoperable, Reusable) and sustainably reusable in research workflows.

The workshop will be led by an interdisciplinary team combining expertise from computer science, digital humanities, and digital archaeology. It is coordinated by the project lead and developer of (semantic) Kompakkt, together with a humanities scholar specialised in archaeology and a professor of digital humanities. This cross-disciplinary constellation ensures that both the technical and scholarly aspects of 3D publishing are addressed.

After a brief introduction to 3D publication standards, metadata practices, and IIIF-based interoperability, participants will receive a guided walkthrough of Kompakkt's main features. The majority of the session will focus on hands-on work, allowing participants to use either their own 3D datasets (Kompakkt supports a wide range of formats: .laz, .las, .spz, .splat, .ply, .spx, .glb, .gltf, .obj, .stl) or provided example models to:

- Upload and publish 3D cultural heritage objects on Kompakkt
- Add and edit descriptive and structural metadata
- Annotate and enrich 3D models with research-relevant information
- Optionally, apply the semantic extension to link 3D content with Wikibase

Throughout the session, participants will discuss challenges, best practices, and scholarly use cases. By the end of the workshop, each participant will have created a personal Kompakkt profile and published at least one annotated and enriched 3D object. It's also possible to publish through embedding on another website.

This workshop directly supports the CAA 2026 focus on open, transparent, and interoperable digital archaeology. It empowers researchers to adopt sustainable publication workflows and contributes to the broader discussion on FAIR data, semantic enrichment, and the long-term accessibility of 3D cultural heritage materials.

#### **Expected outcomes**

- A network of peers working on sustainable, interoperable 3D research infrastructures
- Practical experience publishing, annotating, and enriching 3D data using open-source tools
- Insight into IIIF-based and semantic approaches for 3D documentation
- A reusable workflow for FAIR-compliant 3D data management

## **Chronological modelling with ChronoLog: theory and practice**

*Eythan Levy, University of Zurich*

The workshop will present the foundations of ChronoLog, a free tool for building chronological models, testing their consistency, and computing tight, checkable, chronological estimates. These models consist of a network of entities (e.g. archaeological strata, ceramic periods, historical reigns) connected by a set of synchronisms. The tool allows users to modify the data in the model and assess on-the-fly the impact of these updates on the overall chronology. ChronoLog also allows users to add radiocarbon determinations to their models, and to convert the model automatically to an OxCal Bayesian radiocarbon model. This feature allows archaeologists with no knowledge of the OxCal specification language to build complex Bayesian models on their own, with just a few clicks of the mouse. ChronoLog is freely available for download at (<https://chrono.ulb.be>).

For more details on ChronoLog, a user manual is available on the ChronoLog website. For additional details, see the bibliography below, especially Levy et al. 2021 (Journal of Archaeological Science), and Levy et al., in press (Proceedings of CAA 2021).

The workshop will start with a general introduction to ChronoLog, its basic principles, and its main functionalities. The second part of the session will be devoted to practical modelling exercises, which users will do on their own laptops. In these exercises, users will first learn how to build chronological models by themselves, based on a wide set of archaeological and historical data. They will then explore how ChronoLog can serve as a useful tool for archaeological cross-dating. This part will also present the use ChronoLog as a front-end to OxCal for building Bayesian radiocarbon models. In the final part of the workshop, participants will be invited to present their own data sets, and will be assisted in the modelling of these datasets using ChronoLog

## References

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## Seamless Visualization, Statistical Exploration, and Web Diffusion of Archaeological Spatial Data with the Open-source archeoViz Software Ecosystem

*archeoViz maintenance team, CNRS, CITERES lab., MASA+ consortium, France*

### Why coming?

You have spatialised archaeological data –from excavation archives or a total station–, and you want to explore it quickly and efficiently, make figures and perform statistical analyses for a report, publication or even a public presentation. Time is short and your budget is limited or equal to zero: what can you do?

### How can the archeoViz ecosystem help you?

archeoViz is a stand-alone application designed for the visualization and statistical exploration of archaeological spatial data across multiple scales, from individual objects to excavation sites, landscapes, and entire regions. Tailored archeoViz instances can be deployed online to provide public access to specific datasets. Complementing this, the archeoViz Portal serves as a web application for discovering and browsing references to existing archeoViz instances.

It is important to note that the archeoViz Portal is not a platform for data publication. While the publication of datasets is warmly encouraged, this should ideally be carried out using dedicated, specialized services such as Zenodo, Nakala, ADS, or tDAR.

Learn more about the archeoViz Ecosystem here:

<https://analytics.huma-num.fr/archeoviz/home>

<https://archeoviz.hypotheses.org>

### Expected outputs of the workshop

Join the workshop with your spatialised dataset and, by the end of the day, and depending on your choice you might get:

- figures from your dataset from every angle,
- statistical analysis results,
- or even an online publication of your data and the creation of an interactive website to share with colleagues and local communities.

## InSites: Significance Assessment through the Looking Glass of Gen-AI

*Dr. Yael Alef, Technion, Israel Institute of Technology, Faculty of Architecture and Town Planning*

*Yuval Shafriri, YuValue – Edtech & Heritach consultant*

Articulating significance, which is crucial in value-based heritage management, is a complex interpretive task requiring the synthesis of diverse and fragmented evidence. While Gen-AI offers powerful processing capabilities, delegating this creative process to a machine raises critical ethical concerns.

In this workshop, inspired by Lewis Carroll's novel *Through the Looking Glass*, we navigate this tension by positioning Gen-AI as a reflective partner. Using

our *InSites* Human–AI agentic workflow, we will examine how transformer-based models complement Context-Based Significance Assessment (CBSA), as both fundamentally rely on deep contextual understanding. We move beyond the hype to ask: *Can Gen-AI transparently read and analyze the site documentation so humans can better “read the site” and conserve it?*

We will experiment with transforming site information (from excavation reports, etc.) into a structured assessment process, guiding users through “mini agents” steps in the InSites tool, each with optional training notes for learning purposes. We'll move from detecting missing information and identifying contexts and values to drafting explainable significance statements. Beyond writing, we will experiment with multivocal narratives, knowledge graphs, and interactive views, ranging from standard timelines to novel participant-invented visualizations, that help gain new cultural insights and communicate them in new ways. The *InSites* workflow is grounded in three core Human–AI design principles: *methodological alignment* (embedding professional protocols), *cognitive transparency* and strict *evidence grounding*, which we will explore throughout the workshop sessions.

### Workshop Program

1. **Theory & Demo:** An introduction to the CBSA methodology embedded in the system and how transformer models “mirror” it, followed by a live *InSites* demo.
2. **Hands-On Main Sessions:**
  - **Write with *InSites*:** Co-authoring a significance assessment for a site of the participants' choice alongside the agent workflow, including the generation of visual artifacts and interactive dashboards.
  - **Read with *InSites*:** Analyzing the generated assessments to detect hidden patterns.
  - **Ethics in Practice:** Participants will apply the design principles to experiment with sketching a custom agent for their specific needs.

### Workshop Takeaways

- A preliminary significance assessment report of the site and other generated artifacts.
- Hands-on experimentation with structured Human-AI collaboration workflows.
- Continued access to the *InSites* tool, website, and GitHub repository.

### References

Alef, Y., & Shafriri, Y. (2023). *Cultural Significance Assessment of Archaeological Sites for Heritage Management in the Digital Age: From Text of Spatial Networks of Meanings*. <https://doi.org/10.5281/ZENODO.8360843>

European Archaeological Council. (2025). Assessing Archaeological Significance: Key Concepts (EAC Guidelines 9). European Archaeological Council. <https://doi.org/10.5281/zenodo.10697000>

GitHub Repository: <https://github.com/InSites-Lab/Insites-CAA2026>



## Posters

**Poster session:** Wednesday, 1 April 2026, 10:30-14:30

**Poster exhibition:** Wednesday, 1 April – Friday, 3 April 2026

**Location:** Oktogon

### 9. Sihrhis: a geodatabase of Hellenistic and Roman housing in central-western Sicily

*Giuseppe Monte, University of Catania*

#### Subject

This project develops an open-access geodatabase documenting Hellenistic and Roman domestic structures in central-western Sicily. It integrates fragmented archaeological records (4th century BCE–3rd century CE) into a unified digital framework using Directus for relational database management and GIS for spatial data vectorization. The geodatabase systematically catalogs architectural features, construction techniques, and material culture, enabling standardized cross-comparison and spatial-statistical analyses.

#### Background

Despite numerous excavation campaigns, the domestic architecture of

western Sicilian cities remains underrepresented in digital form. Existing publications often lack systematic spatial encoding, relational linkage, or semantic categorization. The traditional approach emphasizes stratigraphic detail, the stylistic analysis of the architectural remains and site-specific interpretation, without enabling cross-site comparison or diachronic study.

Digital heritage initiatives such as the Getty Institute's ARCHes or SITAR project platforms have demonstrated the potential of open standards and interoperable formats for archaeological documentation. However, these frameworks typically address religious or monumental contexts, leaving domestic data in need of customized solutions.

#### Discussion

The SIHRHIS database is structured using the open-source platform Directus for content management, while the database schema is designed in PostgreSQL and visualized using DBML syntax. The relational model emphasizes interoperability, data normalization, and bibliographic traceability. Key methodological components include the development of a controlled English vocabulary of the terms used, the database architecture and a GIS integration and vectorialization. The first step of the project was the creation of controlled and unambiguous vocabularies addressing the various aspects of the study of domestic architecture. Unique vocabularies were developed concerning the class (e.g. "Reception Room") and function of rooms—favouring, where possible, generic terminology (e.g., "kitchen" instead of "culina")—as well as flooring types and catalogued painting styles.

The relational schema consists of several interlinked tables:

- Houses, Phases, Rooms, and Structures define the spatial and temporal framework.
- Activities, Surfaces, Pavements, and Wall Paintings store qualitative information related to function and decoration.

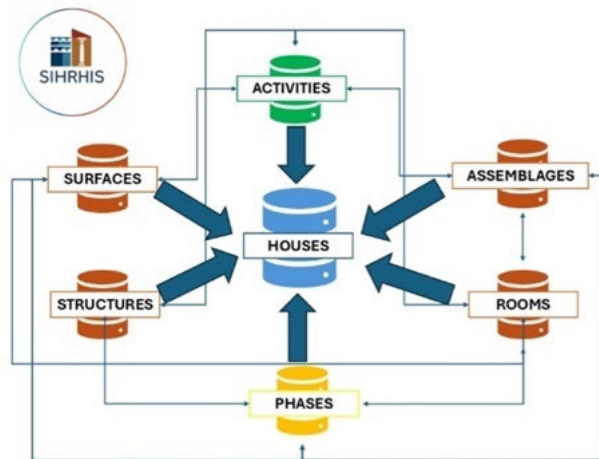
- Assemblages allow material culture to be linked to specific spaces and activities.
- Bibliography and Bibliographic Citations ensure that all data points are explicitly tied to their scholarly sources.

Spatial data is acquired through a custom vectorisation process applied to legacy archaeological plans. For this purpose, SIHRHIS adopts the Simple Vectorisation Protocol (SVP) developed by Julian Bogdani in the context of the PAThs project (Bogdani 2021). SVP is a lightweight, GIS-based method designed to encode architectural and archaeological legacy maps using a minimal yet semantically rich set of attributes.

SIHRHIS is expected to yield several scholarly and methodological contributions:

- Architectural patterns: identification of regional construction trends and spatial organization within domestic units.
- Functional zoning: analysis of how space was used in urban houses based on structural, material, and assemblage data.
- Socio-economic Stratification: quantification of architectural variability to assess status differentiation and household wealth.
- Cultural Hybridity: detection of stylistic and technical features that reflect the interplay of Hellenistic and Roman traditions in housing culture.
- Methodological Advancement: demonstrates how open-source digital tools can support reproducible and transparent workflows in digital archaeology.





## References:

Bogdani, Julian. 2021. "Fieldnotes for the development and publication of open standards for the vectorisation of archaeological and architectonic topographic legacy data". *ArcheoFOSS XIV 2020: Open Software, Hardware, Processes, Data and Formats in Archaeological Research: Proceedings of the 14th International Conference, 15-17 October 2020*: 138-147.

<https://hdl.handle.net/11573/1586913>.

Myers, David, Dalgity Alison, Avramides, Ioannis. 2016, "The Arches heritage inventory and management system: a platform for the heritage field". *Journal of Cultural Heritage Management and Sustainable Development*, 6 (2): 213-224. <https://doi.org/10.1108/JCHMSD-02-2016-0010>

Serlorenzi, Mirella. 2019. "Accessibilità e diffusione del dato archeologico: l'esperienza del SITAR". *Archeologia e Calcolatori*, 29: 31-40. <https://doi.org/10.19282/ac.29.2018.04>

## 48. Counting in Clay: Linking Cuneiform Mathematics and Cultural Heritage in Wikidata

Florian Thiery, LEIZA

Daniel Mietchen, FIZ Karlsruhe — Leibniz Institute for Information Infrastructure

Anja Gerber, Klassik Stiftung Weimar

Daria Stefan, TU Wien

Michael Müller, Humboldt University of Berlin

Dennis Mischke, Free University of Berlin

Marco Reidelbach, Zuse Institute Berlin (ZIB)

Marcus Weber, Zuse Institute Berlin (ZIB)

### Background

Ancient cuneiform tablets preserve some of humanity's earliest records of scientific reasoning, from trade and land surveying to geometry and algebra. Among these, mathematical tablets from the Schøyen Collection represent a unique corpus that documents formulas such as the Pythagorean theorem and Heron's formula in Babylonian sexagesimal notation. Although these artefacts are well documented in catalogues such as the Cuneiform Digital Library Initiative (CDLI), their digital representation across infrastructures remains fragmented. The Wikidata Editathon "Cuneiform meets Mathematics", organised within the DiHMaLab framework, brought together researchers from mathematics, archaeology, and digital humanities to bridge this gap. It aimed to create semantic connections between cuneiform artefacts, mathematical concepts, and modern scholarly interpretations through Wikidata and related Linked Open Data (LOD) environments (Schmidt, Thiery, and Trognitz 2022).

### Subject

This poster presents the methods and results of the editathon, focusing on

how Wikidata can function as an interdisciplinary knowledge hub between cultural-heritage and scientific domains. Participants manually and semi-automatically annotated cuneiform artefacts from the CDLI and the Schøyen Collection with corresponding Wikidata entities representing both the tablets themselves and the mathematical formulas they contain. The work is based on descriptions provided by Jöran Friberg in *A Remarkable Collection of Babylonian Mathematical Texts* (Friberg 2007). A central goal is the automated ingestion of metadata from CDLI for Schøyen tablets into Wikidata, building on these scholarly descriptions. To ensure consistency, the team is developing a unified modelling framework within a dedicated Wikidata Wikiproject. This framework aligns CDLI metadata, mathematical concepts, and bibliographic references with CIDOC CRM entities such as E22 Man-Made Object, while enabling automated RDF export and SPARQL-based validation.

The workflow applies FAIR and LOUD principles:

- extraction and structuring of catalogue data
- semantic alignment of artefacts and formulas
- integration with external ontologies and mathematical vocabularies
- documentation and visualisation using tools such as the SPARQLing Unicorn Toolkit

The resulting dataset allows federated SPARQL queries connecting archaeological, textual, and mathematical information in a machine-actionable form.

#### Discussion

The editathon demonstrates that Wikidata can act as a collaborative bridge between the mathematical and cultural-heritage communities. By semantically linking cuneiform artefacts with mathematical knowledge, it becomes possible to study ancient intellectual practices through a reproducible, data-driven lens.

Beyond the immediate case study, this approach contributes to the creation of interoperable, FAIR-compliant knowledge graphs. It supports larger research infrastructures such as the European Collaborative Cloud for Cultural

Heritage (ECCCH) and the emerging NFDI Knowledge Graph ecosystem (Thiery et al. 2025).

The project illustrates how community-driven modelling, open scripting, and interdisciplinary collaboration can transform specialised datasets, in this case, Babylonian mathematical tablets, into connected, reusable digital research resources. It highlights the potential of Wikidata as a shared environment for integrating scientific and cultural perspectives on the world's earliest mathematics, turning clay tablets into nodes within a living web of knowledge.

#### References:

Thiery, Florian, Lozana Rossenova, Daniel Mietchen, Timo Homburg, und Peter Thiery. 2025. „Distributed Research Data Knowledge Graphs - Challenges of federated queries using the Wikiverse and OpenStreetMap within the NFDI Knowledge Graph Ecosystem“. In *Proceedings of the Conference on Research Data Infrastructure 2025*, herausgegeben von York Sure-Vetter und Paul Groth, 7(5), Q2, 7(5), Q2. Aachen: Squirrel Papers. <https://doi.org/10.5281/zenodo.16736047>

Friberg, Jöran, ed. 2007. *A Remarkable Collection of Babylonian Mathematical Texts: Manuscripts in the Schøyen Collection Cuneiform Texts I. Sources and Studies in the History of Mathematics and Physical Sciences*, edited by J.Z. Buchwald, J. Lützen, J. Hogendijk, P.J. Davis, T. Hawkins, A.E. Shapiro, and D. Whiteside. New York, NY: Springer. <https://doi.org/10.1007/978-0-387-48977-3>

Schmidt, Sophie C., Florian Thiery, and Martina Trognitz. 2022. 'Practices of Linked Open Data in Archaeology and Their Realisation in Wikidata'. *Digital* 2 (3): 333–64. <https://doi.org/10.3390/digital2030019>

## 75. Synchronizing Multilingual Video Data and Visualizing Archaeological Evidence: A Multi-Method Workflow for Track Analysis in a Cave

*Yasaman Piroozfar, FAU CDI*

*Andreas Pastoors, FAU Erlangen-Nürnberg*

*Marcus Walther, FAU CDI*

*Laura Albers, FAU CDI*

This project deals with one of Europe's most extensive sets of Mesolithic human footprints, offering a rare glimpse into human movement around 9,000–8,500 cal BP. During recent documentation sessions, footprint interpretations were provided directly in the cave by indigenous Ju'hoan tracking specialists, whose expertise is rooted in long-standing cultural practices of track reading. Their observations were captured as GoPro video segments, an independent high-quality audio recording in Ju'hoan, and time-aligned transcripts with English translations produced as Word documents and ELAN (.eaf) files. For technical reasons related to field recording conditions and data acquisition, these materials were originally fragmented and unsynchronized, making it difficult to directly connect spoken interpretations to the corresponding visual and spatial evidence.

To overcome this issue, a reproducible digital workflow was developed that synchronizes and integrates these diverse sources into a single, temporally aligned and spatially annotated dataset. The underlying folder structure consists of video and transcript collections divided by cave sector, each containing several recording segments. ELAN annotations were converted to machine-readable XML, enabling the extraction of start and end timestamps, speaker labels, and utterances. These data were then used to automatically generate multilingual subtitles in three formats: original Ju'hoan language, English translation, and bilingual subtitles.

The conversion and subtitle-generation steps were implemented through scripted processing routines that parse ELAN XML files and standardize timestamps across recording segments. These scripts automatically generate subtitle files while preserving speaker attribution and language alignment, enabling consistent processing across multiple cave sectors.

Audio–video synchronization relied on the automated detection of hand-clap events recorded during fieldwork. These events were identified by combining amplitude peak detection with frequency-based analysis to isolate the characteristic acoustic signature of the clap signal. The detected clap peaks were then used as discrete temporal reference points to align the corresponding GoPro video segments with the external audio recordings.

To link verbal interpretations to spatial features within the cave, a laser-based visualization pipeline was introduced. Red and green laser dots, used during recording sessions to indicate individual footprints or movement patterns, were detected using HSV colour filtering and contour detection combined with size-based thresholding. The detected regions were visualized as translucent overlays, providing a direct spatial link between verbal commentary and the referenced footprints.

Each sector-specific video was encoded using FFmpeg to include three subtitle streams, dual audio tracks (original GoPro audio and synchronized external audio), chapter markers for navigation, and structured metadata. This encoding strategy merges text, sound, and image into a consistent and reusable format suitable for analysis, interpretation, presentation, and long-term archiving.

The overall workflow follows a modular, script-based architecture in which audio synchronization, subtitle generation, visual annotation, and final encoding are handled as independent processing steps. This structure allows

individual components to be inspected or adapted without altering the rest of the pipeline, supporting reproducibility and methodological transparency.

The workflow enhances transparency by explicitly linking multilingual verbal interpretations to their original audiovisual context, allowing analytical decisions to remain traceable and verifiable. Spatial clarity is improved by tying narrative explanations to precise visual features, while standardized metadata and formatting support reuse across disciplines such as archaeology, linguistics, and computer science. Beyond its technical contribution, the approach documents how expert interpretations are constructed in the field and provides a practical model for integrating qualitative expertise into reproducible, data-rich archaeological workflows. The methods presented can be adapted to other ethnographic or heritage documentation contexts involving audio, video, and expert narration, supporting interdisciplinary research and open data practices.

### 103. Museum Storytelling based on Knowledge Graphs and Large Language Models

*RIALI Ishak, University Of Blida*

*Raphaël GERSEN, Faculty of Archaeology, Leiden University*

*Elizabeth Rodriguez Estrada, Faculty of Archaeology, Leiden University*

*Gabriel Spautz Vieira, Faculty of Archaeology, Leiden University*

*Martin Berger, Faculty of Archaeology, Leiden University*

Museums play a vital role in preserving and transmitting cultural heritage. However, access to the semantic and historical richness of collections often remains limited to short or technical texts, which are difficult for the general public or those with reading disabilities. This lack of contextualization reduces the educational and emotional impact of the visit, particularly for young people or those with special needs. Furthermore, curators must

manage thousands of objects, often poorly documented, which remain invisible to the public.

The use of advanced technologies such as artificial intelligence gave birth to new perspectives for energizing collections, facilitating the work of curators, and enriching the visitor experience. Among these technologies, large language models (LLMs) stand out for their ability to automatically generate rich and coherent narrative texts, adapted to different contexts. To produce historically reliable narratives, however, these models require a structured and usable information base.

In this context, the authors designed a knowledge graph compliant with the CIDOC-CRM standard, enabling the semantic and interoperable representation of key entities related to museum objects (authors, historical events, locations, periods, collections, etc.), while facilitating the inference and retrieval of complex information. The data used comes primarily from MUDEC's Latin American collections, which contain approximately 7,000 ethnographic and archaeological artifacts spanning different periods and regions.

The proposed system is based on a Graph-RAG (Retrieval-Augmented Generation from a Knowledge Graph) architecture and operates in three stages:

- Extraction of the historical and cultural context of an object from the CIDOC CRM graph.
- Narrative generation guided by a pre-trained LLM, using structured prompts to produce fluent texts while maintaining control over the content.
- Converting text into audio content using a text-to-speech module makes the narration accessible to everyone, including visually impaired visitors.

The evaluation of the narratives by three archaeology specialists revealed differences in performance depending on the language models and criteria analyzed, with factual reliability being a priority to ensure accurate historical and cultural information. The literary style and emotional aspect of the texts were also taken into account.

In conclusion, the use of LLMs allows curators to tell vivid and accessible stories, both for physical and virtual visitors. The integration of text-to-speech improves accessibility and cultural inclusion. However, the quality of the data and generated texts must be verified by experts, as AI hallucinations may occur. Finally, the use of varied prompts could diversify the narrative "voice" of exhibitions, offering stories adapted to different audiences.

## 115. Spectrify.app: Evaluating a Browser-Based Platform for Spectral Analysis

*Rubén Parrilla, ICArEHB*

Managing spectral data from archaeological and heritage materials remains difficult. Researchers use different techniques—FTIR, Raman, UV-Vis-NIR—each requiring specialized processing. Most software demands installation, programming skills, or expensive licenses, creating barriers that prevent many archaeologists from using chemometric methods despite their proven value for pigment analysis, provenance studies, and conservation work.

We evaluated Spectrify, a in development browser-based application built to simplify spectral analysis. The platform combines multiple analytical techniques in one interface, runs locally to protect unpublished data, and needs no installation. We tested whether Spectrify could match results from established Python libraries (ChemoTools, Scikit-Learn) by replicating published chemometric procedures.

Two validation tests were conducted: first, we reproduced preprocessing and multivariate analysis workflows from published archaeological spectroscopy papers; second, we directly compared Spectrify's algorithms against equivalent Python implementations. We assessed result accuracy, workflow ease, and usability for researchers without programming experience. Spectrify replicated published results even when using slightly different preprocessing choices (MSC versus SNV standardization, for example). PLSR

models built through the interface performed as well as code-based versions. The menu system allowed quick hyperparameter testing and dataset combination without coding. Workflow files (.spws format) enabled reproducibility, which matters for archaeological research where methods need transparent documentation.

Browser-based platforms change how archaeologists access analytical methods. Removing technical requirements while keeping analytical standards lets researchers concentrate on interpretation instead of software problems. Local processing protects sensitive heritage data that cannot be shared before publication.

Accessible spectral platforms can spread quantitative characterization beyond specialized labs. . As archaeometric data grows, tools that balance accessibility with analytical rigor will shape how the field engages with computational methods.

## 116. Portable Spectroscopy for Pigment and Binder Characterization: A Reflectance Spectroscopy Evaluation

*Rubén Parrilla, ICArEHB*

Spectroscopic methods remain uncommon in archaeological research despite their proven utility. Raman spectroscopy has gained some acceptance for analyzing individual objects, and laboratory FTIR is increasingly used, but other techniques lag behind. Colorimetry, hyperspectral imaging, and infrared reflectance are standard in remote sensing but rarely applied to archaeological materials. Portable spectroscopy offers clear benefits: in situ measurement, non-destructive analysis, fast data collection, and compatibility with chemometric analysis. We evaluated portable spectroscopic methods to assess their practical value for archaeological materials.

We analyzed synthetic and natural mineral pigments mixed with five protein binders: bone glue, fish glue, hide glue, gelatin glue, and rabbitskin glue. Pigments included synthetic red, synthetic yellow, natural red, and natural yellow. This combination created a difficult classification problem because the binders have similar spectral properties. Each sample mixed 500mg pigment with 2.5ml dissolved binder.

Two instruments were tested: an ASD Halo Terraspec spectrometer (350-2500nm, 2150 bands) and a Headwall Photonics SWIR hyperspectral camera (900-2500nm, 160 bands). We measured each sample three times. Hyperspectral data used 70×70 pixel areas, giving 4900 spectra per sample. Processing included SNV transformation, Savitzky-Golay smoothing, and normalization. We calculated first and second derivatives and used PCA for classification (Cruse, Hall, and Thennadil 2021).

The spectrometer successfully classified binders. Visual spectrum data showed some overlap between rabbitskin, hide, and bone glue, but SWIR regions separated them clearly. Mineral identification found hematite in red pigments and goethite in yellow ones. Hyperspectral analysis showed intensity and peak differences between binders, especially above 1300nm. PCA worked well for natural red samples. False color images using selected wavelengths revealed compositional differences within samples.

Portable spectroscopy can distinguish pigments with different binders, which matters for archaeological interpretation. Similar workflows apply to ceramics, lithics, and other materials. Hyperspectral cameras add spatial analysis, showing how composition varies across surfaces. The speed and non-invasive nature make these methods practical where sampling is restricted. As equipment becomes cheaper and processing simpler, spectroscopic characterization may shift from specialized labs to routine fieldwork, expanding what archaeologists can analyze without laboratory access.

## References:

Cruse, Simon, Benjamin Hall, and Suresh N. Thennadil. 2021. "Cluster Analysis for IR and NIR Spectroscopy: Current Practices to Future Perspectives."

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## 117. Spacialist: Collaborative research data management in heterogeneous multi-workgroup research projects

*Severin Opel, Universität Tübingen, DHC*

*Martin Offermann, Leipzig University, Institute of Geography*

*Vinzenz Rosenkranz, Tübingen University, DHC*

*Geraldine Quénehervé, Tübingen University, DHC*

*Christoph Zielhofer, Leipzig University, Institute of Geography*

*Michael Derntl, Universität Tübingen, DHC*

Large-scale collaborative research projects with an interdisciplinary approach inherently incorporate a high level of heterogeneity in methodological approaches and vocabularies, especially when the teams are geographically dispersed. These preconditions can lead to inconsistent terminologies and structures in research data, making comparability and synthesis difficult, if not impossible. With Spacialist, a virtual research environment, we address these challenges by enabling the definition of a shared data model and controlled vocabulary. This approach minimizes human error and ensures consistency and comparability across projects. In addition, it provides collaborative tools for a modern multi-user experience.

When the first prototype of Spacialist was presented at CAA 2017 (Lang et al. 2020), its requirements focused primarily on archaeological research. Since then, the software has evolved into a more flexible research tool with a powerful plugin system that enables modular functional extensions. In this poster, we focus on new functionalities implemented to support large collaborative projects involving members distributed across multiple sub-projects. These include (1) a new access control system that allows assigning



user accounts to different workgroups with separate access rights; (2) real-time data synchronization via the WebSockets protocol for immediate data updates; (3) a commenting system that allows discussion directly at individual data points; (4) a bibliography system for collaborative literature management; and (5) metadata management for copyrights and licensing.

These collaboration features were implemented as Spacialist serves as the central data management platform within the DFG Priority Programme 2361 “On the Way to the Fluvial Anthroposphere”, which studies the human impact on floodplains of several rivers in Germany. The project is highly heterogeneous: comprised of seven sub-projects at different institutions; researchers come from a broad spectrum of fields such as geography, archaeology, and history; and they work on multiple sites across Germany. Therefore, we use the SPP 2361 as a case study to demonstrate how Spacialist can support large, heterogeneous research projects.

#### References:

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## 121. Quantifying Knapping Kinematics: Applying DeepLabCut to Analyse Bipolar and Freehand Knapping Methods

*Agata Gaszka, ICArEHB, Universidade do Algarve*

*Li Li, ICArEHB, Universidade do Algarve; Department of Human Origins, Max Planck Institute for Evolutionary Anthropology, Leipzig, 04103, Germany*

*Tomos Proffitt, ICArEHB, Universidade do Algarve*

The ability to intentionally create and use sharp stone tools was a watershed moment in hominin evolution, allowing our ancestors to interact with and modify their environment in unprecedented ways. Bipolar knapping represents a crucial yet understudied component of early lithic technologies. It has been hypothesised that hominin stone flaking developed from a culture of percussion similar to behaviours observed in modern primates, such as nut cracking (Davidson and McGrew 2005). Both bipolar knapping and nut-cracking involve using a hammerstone to strike an object placed on top of an anvil. The ability to generate suitable kinetic energy and transmit it to a specific point of impact may also be a common aspect of these behaviours. It has been suggested that bipolar knapping may have represented a simpler form of flake production, emerging from a previous culture of percussive activity using stone tools (Hayden 2015).

To evaluate whether bipolar knapping represents an intermediate stage between non-flaking percussive behaviours and freehand flake production, we conducted a quantitative comparison of knapping motions between freehand and bipolar techniques. We used DeepLabCut, an open-source deep learning toolbox for markerless pose estimation, to extract motion data from video recordings of experimental knapping sessions (Mathis et al. 2018). Key points on the knapper’s upper body, including the digits, wrist, hand, elbow, shoulder, and hammer, were tracked to capture time-resolved 2D motion coordinates. These data were then used to calculate relevant kinematic

parameters such as hammer swing trajectory, strike velocity, acceleration, and kinetic energy. Our results reveal clear differences in key aspects of knapping motion between the two techniques, demonstrating the potential of DeepLabCut for reliable pose estimation in knapping experiments and establishing a replicable framework for investigating the biomechanical and evolutionary implications of early stone tool technologies.

#### References:

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## 126. Settlement preferences of ancestral Pueblo culture in American South West region

*Dorian Kominek, Independent*

The topic of this analysis was to identify and quantify the settlement preferences of the Ancestral Pueblo settlement complex (Pueblo III period, Sand Canyon area in South West USA).

The research question was to find these preferences, as a quantitative data patterns, that can be extracted using various GIS analysis. Furthermore, this would be the initial step to perform the comparison analysis of these

patterns for other settlement complexes recognised in archaeological record for mentioned culture in this region.

Poster shows the steps and results of the analysis with the GIS geoprocessing tools and workflows. Data used for analysis was received from the archaeological surveys done in multiply sites in that area. Also the open access resources were used for the landscape and geographical data.

Using the ArcGIS software and its geoprocessing tools, the georeferenced 3D model of this area was created as a base for analysis, from the combination of the digital elevation model, settlements location with their attributes and water streams courses.

With the different types of settlements recognised by the archaeological record (the main settlement, dwellings, watchtowers, shrines ) the following analysis were performed, targeting each type of settlement in a separate take: Viewshed, Availability analysis, water distance, and the finest travel path.

Result values for each one settlement were put together to count statistics and verify what general rules can be extracted.

#### Discussion

Metrics and statistics of the parameters received from these analysis, refer only to the one settlement complex. Even that direct values can be found interesting, they are mainly the results of the modeling output only, and can't be easily validated on the ground level accuracy. The most valuable outcome of presented set of analysis would be achieved when they are also applied to other settlement complexes known in archaeological record in this region. The comparison analysis of such results would bring additional knowledge in the research of the settlement systems dynamics.

#### References:

Palonka R., 2019. „Towers as an Architectural Element of Pueblo Culture in the Mesa Verde Region, Utah-Colorado, in the 12th-13th Century A.D.” in: *Tower Studies 3 'Urbs turrita'*, Shaun Tyas Donington.

Lipe W. D., Varien Mark D., 1999. "Colorado Prehistory - A Context for the Southern Colorado River Basin", chapter 9 - "Pueblo III (A.D. 1150-1300)", 290-518.

## 140. Evaluating Datasets and Comparing Machine Learning Approaches for Archaeological Pottery Classification

*Nikhil Sabnis, Nueva School*

The advent of computational techniques [1,2] in recent years has significantly impacted the quality of image classification within the field of archaeology. New models of machine learning, including sophisticated artificial neural networks (ANN), have become increasingly prevalent, providing researchers a wide array of computational tools to consider. While purpose-built ANNs have demonstrated accurate results (e.g., Zhao et al., 2023 reported 92.58% accuracy on Chinese pottery using custom CNNs [3]), these models can require considerable expertise and fine-tuning to achieve superior results. This study evaluates open access pottery datasets and compares the outputs of simple machine learning models with advanced, more resource-intensive models based on ANNs, providing a framework for model selection and a deeper understanding of the benefits and challenges of implementing these varied approaches.

In our study, we evaluate several open archaeological pottery image datasets, documenting their organization, image quality, and suitability for machine learning. Using the Chinese Neolithic Painted Pottery dataset [3] along with other publicly-available datasets, I implement classical machine learning approaches including Random Forest and Support Vector Machines, drawing on extractable image features, including color patterns, textures, and basic shapes. Results across these models are compared to published deep learning studies to show the performance difference between accessible methods and cutting-edge approaches. Implications of the benefits and challenges faced by researchers implementing these varied computational

models are discussed. This study further contributes to research on increasing the accessibility of computational models for classifying archaeological artifacts.

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- (2) Verschoof-van der Vaart, Wouter B., and Mark R. Lambers. 2021. "Machine Learning Arrives in Archaeology." *Advances in Archaeological Practice* 9 (2): 186–91. <https://doi.org/10.1017/aap.2021.6>.
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<https://doi.org/10.1016/j.daach.2023.e00269>.

## 151. Quantifying morphometric variability in bead production. First results of a digital study of Double Perforated Ivory Beads from Aurignacian layer IV of Hohle Fels Cave (Germany)

*Shuqin Guo, The University of Tübingen*

*Marian Vanhaeren, CNRS, UMR 5199 PACEA, University of Bordeaux, France*  
*Sibylle Wolf, Dept. of Early Prehistory & Quaternary Ecology, Univ. of Tübingen; Senckenberg Centre for Human Evolution & Palaeoenvironment, Tübingen, Germany*

*Nicolas Antunes, Deutsches Archäologisches Institut, Archäoinformatik, Im Dol 1-3, 14195 Berlin, Germany*

*Nicholas Conard, Dept. of Early Prehistory & Quaternary Ecology, Univ. of Tübingen; Senckenberg Centre for Human Evolution & Palaeoenvironment, Tübingen, Germany*

Double perforated ivory beads (DPIBs) represent a unique element of the Aurignacian ornament assemblages of the Swabian Jura where hundreds of them have been found at four different sites (Wolf, 2015). But are all these DPIBs the same or can we identify individual craftspeople, chronological or regional trends? In order to enable detailed systematic comparisons between numerous fragile DPIBs, we developed a relatively seamless and conservation friendly method to automatically extract morphometric parameters from 2D flatbed scans of the beads.

Frontal and lateral views of DPIBs were scanned at a resolution of 1200dpi/inch with a high-standard flatbed scanner. Using image processing software, all views were assembled in plates and transformed into black and white silhouettes from which bead contours could be automatically recognized and vectorized. The vectorized contours were then extracted and analysed in R. Morphometric variables included surface area and -perimeter, maximum-, minimum- and mean radius as well as the standard deviation of the radii and ellipse eccentricity. A multivariate analysis has been applied to explore patterns in the data set obtained.

Application of this method to the Aurignacian DPIBs assemblage from Archaeological Horizon IV at Hohle Fels Cave (Swabian Jura, southwestern Germany) reveals important differences in size, shape and degree of symmetry of DPIBs.

Determining the reasons for this variability is challenging. First the data acquisition must be checked for errors as 3 dimensional beads may have been scanned in slightly different oblique positions resulting in biased silhouettes, contours and morphometrics. Second, morphometric variability of manufactured beads, may not only depend on chronological and geographical variations but also on multiple other mutually influencing factors such as the

characteristics of raw materials used, the stage of production, the skill, aim, and time investment of the maker, as well as the potential impact of the physical and social environments (cf. e.g. Schiffer & Skibo 1997, Ferguson 2008). A promising way to disentangle these contributing factors is to compare the morphometric variability of archaeological craft products to numerous reference collections for which at least one influencing factor is known. By generating target-specific outline images, extracting them in R, and applying computational methods, we can quantify the morphological and morphometrical features of numerous ornaments from archaeological and experimental reference collections and as such create a tool for a better understanding of morphometric variability, standardization and crafts in the archaeological record. Future research may also include automatic landmark positioning for outline regularity analysis and test if 3D morphometric analyses allows to reach similar or different results.

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- [2] Schiffer, Michael Brian, James M. Skibo, 1997. The Explanation of Artifact Variability. *American Antiquity* 62(1): 27-50.
- [3] Wolf, Sibylle. 2015. *Schmuckstücke: Die Elfenbeinbearbeitung im Schwäbischen Aurignacien*. Tübingen: Kerns Verlag.

## 153. Reviving the Vanished: Digital Reconstruction of Targovska Street's Urban Heritage

*Nikolay Petkov, IICT-BAS*

*Miglena Raykovska, IICT-BAS*

*Ivaylo Nachev, IBS-BAS*

*Vladimir Kolev, UACG*

Targovska Street was one of the principal commercial and cultural arteries of early twentieth-century Sofia, Bulgaria, symbolising the city's transition toward a modern European urban identity. The area was entirely destroyed during the bombing of Sofia in 1944, resulting in the loss of a major architectural and social landmark. Only fragmentary archival materials—drawings, photographs, and cartographic sources—preserve its memory. The scarcity and uneven quality of these sources pose significant challenges for accurate reconstruction, especially in an era when AI-generated models are increasingly produced by non-specialists, often lacking historical or architectural contextualisation.

The research employs 3D architectural modelling integrated with advanced computational methods to reconstruct and interpret the lost urban heritage of Targovska Street. Machine learning and computer vision algorithms were applied to enhance degraded historical imagery, identify recurring architectural typologies, and support data integration. Based on systematically analysed documentary evidence, the study reconstitutes the street's architectural rhythm, volumetric composition, and stylistic diversity. The resulting 3D models are embedded in an immersive virtual environment, enabling interactive exploration of the reconstructed streetscape and fostering both scholarly analysis and public engagement. The workflow combines geometric precision and photorealistic rendering to achieve analytical robustness and experiential realism.

The project demonstrates how AI-assisted 3D reconstruction can function as both a scientific and interpretive instrument within digital archaeology. By reconstructing a completely lost urban landscape, it illustrates how computational methods can recover and reinterpret cultural memory through historically grounded visualization. At the same time, it underscores the importance of expert knowledge in guiding the reconstruction processes to prevent aestheticised but historically inaccurate outcomes. The case of Targovska Street highlights the potential of artificial intelligence, when critically employed, to integrate heterogeneous data sources into coherent virtual

environments, advancing computer applications in archaeology from documentation toward interpretive historiography.

## 172. Towards a digital continuum of archaeological knowledge: from acquisition to processing to consultation of data

*Anna Maria De Luca, Università di Catania*

The use of digital tools in archaeology does not merely represent an operational improvement but now establishes a true methodological transition towards the construction of integrated systems for archaeological data management and analysis. In this perspective, archaeological data become part of a production and management flow organized according to shared, traceable, and verifiable protocols. Within this framework lies the archaeological context of Castiglione di Sicilia (Contrada Acquafredda–Imbischì, Province of Catania) (Pappalardo et al. 2023, 3–19), which represents a case study of the integrated application of artificial intelligence and digital technologies, from data acquisition in the field to their processing and publication.

The overarching objective is the construction of a unified platform capable of coherently connecting excavation documentation, data management, material organization, and the dissemination of research results, ensuring full interoperability between work environments and publication systems. The model developed for Castiglione di Sicilia is based on an integrated structure designed to interact with different systems—such as GIS, relational databases, and web platforms—while maintaining a consistent semantic structure throughout the entire research process. Information traceability is ensured through the adoption of open standards and univocal recording procedures, which make it possible to accurately reconstruct the origin and use of data.

The operational process is articulated into four main phases: acquisition, processing, enrichment, and publication. During the acquisition phase,

topographical surveys, photographic data, stratigraphic annotations, and excavation diaries are produced in order to maintain full correspondence between direct observation and digital recording, working directly in the field. The processing phase organizes data according to controlled schemas and vocabularies, ensuring both semantic and chronological consistency. Enrichment takes place through the integration of datasets within interoperable environments and the association of descriptive and spatial metadata. Finally, the publication phase delivers the research results through interactive interfaces and online consultation tools (D’Andrea 2023, 32).

Artificial intelligence is applied in two main areas: the visual component, through computer vision systems used for the pre-classification of materials, allowing for an initial automatic organization of images based on morphological and typological criteria of ceramic data; and the textual component, through generative language models that support the automatic drafting of forms and excavation diaries, producing coherent compilations consistent with the adopted descriptive standards (Gattiglia 2025, 225–233). Furthermore, an identity and role management system has been implemented to regulate data access and modification levels within the program, ensuring security, traceability, and authenticity of processes.

The experimentation conducted at Castiglione di Sicilia serves as a testing ground for establishing an information flow between excavation, storage, and digital data collection, offering a methodological reflection on the role of new frontiers in archaeological research and on the integration of artificial intelligence languages. It reaffirms the path toward a new epistemology and a renewed methodological and archaeological approach.

## 203. Cultural Heritage in FAIRyland? How to LODify Geo-Data in QGIS

*Florian Thiery, LEIZA*

*Brigit Danthine, Austrian Archaeological Institute*

*Nadine Alpino, Schleswig-Holsteinische Landesbibliothek*

### Background

Teaching Linked Open Data (LOD) concepts in archaeology and cultural heritage (Schmidt, Thiery, and Trognitz 2022) often faces the challenge of bridging abstract semantic models with practical geospatial workflows. To address this, the FAIRyland (Thiery, Danthine, and Alpino 2025) project introduces a fictional but geographically inspired training landscape located “somewhere near Sweden during the Minion Period.” Its topography draws inspiration from the rock carvings of Norrfors on the Ume River near Umeå in Västerbotten, Sweden (Älvdal 2025). Within this playful setting, archaeological, mythological, and imaginary features coexist to provide an accessible learning environment for FAIR data management, semantic modelling, and QGIS-based geoprocessing.

### Subject

The poster presents FAIRyland as an open, narrative-driven sandbox to demonstrate how the FAIR principles – Findable, Accessible, Interoperable, and Reusable – can be applied to geodata using the SPARQLing Unicorn QGIS Plugin. Vector layers representing sites such as meteor craters, ancient roads, and mythical “input zones” are semantically enriched with Wikidata identifiers and converted into RDF triples.

The workflow illustrates how QGIS can be used not only as a GIS tool but as a FAIRification environment: (1) Structuring geospatial attributes according to shared vocabularies; (2) Transforming datasets into LOD; (3) Querying distributed endpoints such as Wikidata or the NFDI4Objects Knowledge Graph; and (4) Automatically generating human-readable HTML documentation. All



datasets and scripts are openly available on GitHub, inviting collaboration and creative reuse.

#### Discussion

FAIRyland demonstrates that fictional yet technically valid datasets can effectively teach geoinformatics and semantic interoperability in archaeology. By gamifying complex LOD concepts, the approach lowers entry barriers for students and researchers, promoting reproducible, open, and linked workflows.

The combination of real-world topography (inspired by Norrfors) and creative data modelling exemplifies how pedagogical design, semantic web tools, and cultural heritage narratives can merge into an engaging educational framework.

Ultimately, FAIRyland is both a methodological playground and a community-driven experiment in FAIR and LOD data literacy, encouraging archaeologists to explore how open geodata, storytelling, and semantic technologies can work together to make digital heritage more connected, comprehensible, and fun.

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Schmidt, Sophie C., Florian Thiery, and Martina Trognitz. 2022. 'Practices of Linked Open Data in Archaeology and Their Realisation in Wikidata'. *Digital 2* (3): 3. <https://doi.org/10.3390/digital2030019>.

Thiery, Florian, Brigit Danthine, and Nadine Alpino. 2025. 'FAIRyland'. *Squirrel Papers* 7 (2): λ5. <https://github.com/Research-Squirrel-Engineers/FAIRyland>.

## 210. Siamese Networks for the Recognition of Rare Classes in Archaeological Fine-Grained Ceramics

*Federica Mauro, University of Pisa*

*Franco Cicirelli, ICAR CNR*

*Ettore Ritacco, University of Udine*

*Gabriele Gattiglia, University of Pisa*

#### Subject

This study explores how Siamese neural networks can address class imbalance in fine-grained archaeological ceramic classification by focusing on relationships between images rather than fixed labels.

The dataset comprises about 10,000 images of decorated majolicae from Montelupo Fiorentino (Italy), across 86 classes, and shows a pronounced long-tail imbalance, with many rare classes represented by fewer than ten instances (Anichini et al. 2021).

This pattern reflects the archaeological record: common types dominate excavation contexts, while rare or transitional artifacts are underrepresented. Although archaeologists can interpret these categories as signs of changing tastes, production shifts, or declining craftsmanship, standard neural networks tend to overlook the subtle visual traits that define them.

#### Background

In supervised image classification, optimization is dominated by majority classes, making minority categories difficult to learn.

Siamese networks overcome this limitation through metric learning, training on pairs of images instead of isolated samples (Bromley et al. 1993). Each branch shares weights and produces an embedding vector whose distance encodes similarity between artifacts.

To stabilize feature learning, each image is augmented, teaching the network that different versions of the same artifact remain equivalent.

Through a contrastive-loss function, the model pulls similar samples closer and pushes dissimilar ones apart, creating a feature space where fine-grained stylistic similarities become measurable.

#### Discussion

A baseline ResNet-101 model trained on the same dataset achieved an accuracy of 0.73, a weighted F1 of 0.73, and a macro F1 of 0.62, confirming good overall performance but weak recall for rare decorations. Several minority classes showed recall below 0.50 and F1 near zero due to few instances and high visual overlap with frequent motifs, causing the drop in macro recall (0.64).

The Siamese framework directly addresses this limitation by reframing classification as similarity learning, improving consistency across rarity levels. Although widely used in computer vision and few-shot learning, Siamese networks remain rare in archaeology (an example in Chaowalit et al. 2025); this study presents their first large-scale, fine-grained application.

The approach is inspired by the fact that learning in dissimilarity spaces mirrors human categorization through recognition by resemblance, an idea closely aligned with archaeological typology.

By modeling similarity and dissimilarity, Siamese embeddings reveal visually stable categories and expose ambiguous ones, such as low-quality productions or transitional phases. Finally, assessing such class robustness model uncertainty into archaeological insight and offering a new way to study variation and the cognitive logic of classification in material culture.

#### References:

Anichini, Francesca, Nachum Dershowitz, Nevio Dubbini, Gabriele Gattiglia, Barak Itkin, and Lior Wolf. 2021. "The Automatic Recognition of Ceramics from Only One Photo: The ArchAIDE App." *Journal of Archaeological Science: Reports* 36: 102788.

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Bromley, Jane, James Bentz, Léon Bottou, et al. 1993. "Signature Verification Using a 'Siamese' Time Delay Neural Network." *International Journal of Pattern Recognition and Artificial Intelligence* 7 (1): 25–54.

<https://doi.org/10.1142/S0218001493000339>.

Chaowalit, Orawan, Pitikan Kuntitan, Patipan Watjanapron, and Saowalak Arampongsanuwat. 2025. "Application of Siamese Network to Classify Small Dataset of the Motifs on the Center of Sukhothai Ceramics." *ICIC Express Letters, Part B: Applications* 16 (5): 463–69.

<https://doi.org/10.24507/iciclb.16.05.463>.

## 241. After 75.000 Years Still Here - reconstruction of Paleolithic fishing nets, with help of the internet

*Jadranka Ahlgren, Studio JI*

#### Background

What inspired me was the reconstruction of Paleolithic fishing nets with the help of indigenous people from New Guinea, the Amazon, and the Nazca culture in Peru, 200 BCE - 600 AD. The Nazca ceramic I found at <https://art.thewalters.org/object/48.2865/> - The Walters Art Museum. The Nazca people were fishing with nets around their backs, swimming! They often wear fishing nets around their heads, too, like turbans. We see similar in the Mantava indigenous people from New Guinea - YouTube: Best Ever Food Review Show, episode Eating With the World's Most Isolated Tribe (Papua), 2024. <https://www.youtube.com/watch?v=FtWJPyACc>

#### Goal

Analyze the Paleolithic diamond fishing net pattern as a new technology, a result of the functional and practical mind, not symbolic ones! Fishing nets from the Paleolithic had shell weights, and the punctuated shells found at

the same sites can be weights, not jewelry - personal ornaments (Stein S, Pacheco S, 2025).

#### Method

Surfing the internet. Before the internet /time with a lack of information/, it was hard to make a study like this. As a designer, I investigated patterns and ornaments workings mostly with a database of my own memory! Today, we have an enormous accumulation of knowledge, which choice is not ours, and in that field, we can easily miss interpretation! For me, individual investigation is the priority.

#### Discussion

Man is creative, rational, and practical. The diamond-shaped nets are stronger than others; one could hold them around a body and have hands free for work! In my search, I found parallels like “Nazca fishing caps (turbans)” and the Paleolithic Italian shell-caps found in Gravettian cave graves, 20.000 BC: “Lady of Cavilione” and “Prince of Arene Candide”. “Lady” and “Prince” had shell-beaded caps, described by archaeologists as symbolic features and jewelry! (Chavalier T, 2018; Pettitt P, Richard M., 2015). I disagree with that! I think these caps are personal fishing nets of fishing mastes! Similarly, I found two Vinca culture Neolithic figurines, dated to 4500 BCE, from the site of Vitkovac, Central Serbia, with fishing nets around their hips (Ahlgren J, 2005). I think they are not “Ladies” but master fisherwomen!

#### Conclusion

75.000 years, after diamond net, abstract, cross-heckled engravings in Blombos ochra stones (Stein S, Pacheco S, 2025), we have the same nets today! Why? Because they are good! Net-like construction holds pressure with all surfaces simultaneously and is strong. Paleolithic man noticed that.

#### References:

Stein S. and Pacheco S, 2025: Did Fishing Nets with Shell Weights Precede the Bow and Arrow in Brain Evolution? Using Digitally Edited Photographs

to Model Another Use for Prehistoric Shell Beads [https://www.academia.edu/128597855/Did\\_Fishing\\_Nets\\_with\\_Shell\\_Weights\\_Precede\\_the\\_Bow\\_and\\_Arrow\\_in\\_Brain\\_Evolution\\_Using\\_Digitally\\_Edited\\_Photos\\_to\\_Model\\_Another\\_Use\\_for\\_Prehistoric\\_Shell\\_Beads](https://www.academia.edu/128597855/Did_Fishing_Nets_with_Shell_Weights_Precede_the_Bow_and_Arrow_in_Brain_Evolution_Using_Digitally_Edited_Photos_to_Model_Another_Use_for_Prehistoric_Shell_Beads)

Chavalier T, 2018: Trauma in the upper limb of an Upper Paleolithic female from Caviglione cave (Liguria, Italy): Etiology and after-effects in bone biomechanical properties <https://www.academia.edu/89122430/>

Pettitt P, Richard M, 2015: The Gravettian burial known as the Prince (“Il Principe”): New evidence for his age and diet <https://www.researchgate.net/publication/30054509>

Ahlgren J, 2005: Poster for Session 3, EAA 2025 Belgrade, with Abstract – final version <https://www.academia.edu/142903245/>

## 251. The CiVers-Project. Bridging research texts and (fine-grained) research data

*Marcel Riedel, German Archaeological Institute*

*Fabian Riebschläger, German Archaeological Institute*

#### Background

Research data are central components of archaeological knowledge production, yet they are – when published - often cited only indirectly or at the level of the entire databases rather than as fine-grained, reusable research objects. In everyday archaeological practice, researchers may wish to cite a specific pottery sherd from a collaboratively maintained object catalogue, a particular stratigraphic context from excavation documentation, or a defined version of a record whose interpretation may change over time. Without persistent, version-aware identifiers, such references are difficult to reproduce, verify, and reuse.

Persistent identifiers (PIDs) such as DOIs have become a de facto standard for scholarly publications and research data. Through infrastructures such as DataCite and Crossref, DOIs are embedded in a wider network (“PID Graph”) that connects publications, data, researchers, institutions, and citation events (Fig. 1). However, integrating these mechanisms into semantic, collaboratively updated archaeological (web) databases remains a significant challenge.

### Subject

The CiVers project addresses the problem of persistent, fine-grained citation in semantic data systems without requiring fundamental changes to existing software architectures or data models. Archaeological databases often rely on semantic models and authority data and are continuously updated by multiple contributors, making it difficult to assign stable identifiers to specific resource states or versions.

CiVers provides a reusable, open-source information infrastructure that enables PID-supported citation by combining web archiving techniques, machine-readable metadata extraction, and integration with open DOI registration and metadata services (e.g. via DataCite). CiVers captures citable snapshots of web resources and links them persistently into the global PID ecosystem. The system is currently under active development (minimum viable product) and is being deployed and evaluated locally as a service for archaeological information systems, including iDAI.objects (object catalogues) and iDAI.field (excavation documentation). These deployments serve as quality test cases for fine-grained citation of individual records and their evolving interpretations.

### Discussion

For archaeology, CiVers contributes directly to improved reproducibility, data reuse, and scholarly communication. By enabling persistent references to specific versions of archaeological records, the approach supports transparent citation practices across publications and data published or shared via web-databases. This strengthens FAIR-aligned workflows and facilitates

quantitative and comparative analyses that depend on clearly identifiable source data.

More broadly, the project addresses a key infrastructure challenge: the quality of interconnection within global information infrastructures depends on the extent to which relationships between self-hosted and external resources are represented through machine-readable metadata (Fig. 1). CiVers is developed in close dialogue with domain-specific initiatives, consortia, and information and library services, combining technical development with community-oriented evaluation of citation workflows.

The poster will present CiVers architecture, citation workflows, and concrete archaeological use cases. It aims to engage with other archaeological database providers, gather further requirements from diverse contexts, and foster collaborative adoption of persistent citation practices within the archaeological community.

### Reference:

Riedel, M., F. Riebschläger, and G. Russo. 2025. “World.” Forum for Digital Archaeology and Infrastructure, June, 1–34.  
<https://doi.org/10.34780/6k764r03>

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<https://doi.org/10.34780/4qjy3nf4>

Lukas Grüning et al. 2025. “CiVers: Versionierte Webzitation leicht gemacht!” YouTube video, 9:55. November 11, 2025.  
<https://www.youtube.com/watch?v=Jje8Kb8xJL0>

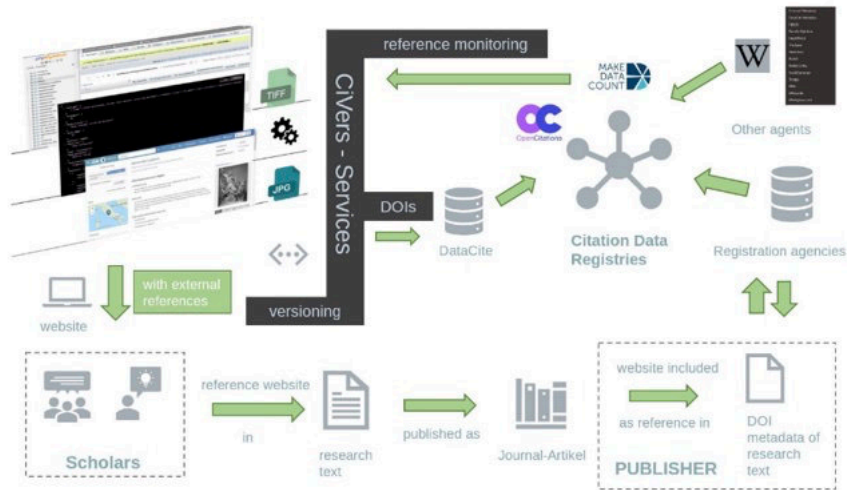


Fig. 1: Schema: CIVERS in a nutshell

## 263. Let the 3D model meet the narrative. A workflow for creating a 3D edition of a tambourine player figurine for archaeology education

*Federica Di Biase, University of Cyprus*

Digital storytelling solutions centred on 3D volumes are gaining increasing attention in cultural heritage presentation and have been recognised by experts as rewarding practices for disseminating their work in non-traditional formats.

In this poster, I will discuss the theoretical and practical workflow for publishing the 3D edition of a terracotta tambourine player figurine stored at the

Natural History Museum of Cyprus in PURE3D, an infrastructure for the publication and preservation of 3D scholarship.

The 3D edition of the tambourine player figurine serves to test and critically assess a publication pipeline grounded on participatory design theory and digital storytelling principles, while also exploring its potential as a pedagogical resource for teaching archaeology to BA and MA students in archaeology and cultural heritage fields. By promoting an object-based learning approach, the 3D edition claims to stimulate curiosity and also encourage deeper engagement between students and the museum context in which the artefact is preserved.

The workflow entailed four main steps: (1) creation of the 3D model and the 3D edition, (2) iterative improvement of the edition, (3) testing, and (4) evaluation.

Semi-structured interviews with museum professionals, including a museum director, curators, archaeologists, and education officers (n=8), informed the first three stages of the process, from object selection to content design, refinement, and testing. This participatory approach ensured that the resulting 3D edition aligns with institutional needs and curatorial perspectives.

The fourth stage of the work entails the use of an online questionnaire, currently still open, to assess students' perceptions of the narrative structure, the contribution of multimedia content to understanding archaeological information, and the effectiveness of the 3D edition in supporting the learning of key topics. Preliminary observations suggest that students report high levels of enjoyment and perceived learning, indicating the potential effectiveness of this approach for archaeology education. Moreover, the results of this evaluation will inform the iterative refinement of the digital edition, promoting active student participation in the co-creation of educational content.

### References:

Barratt, R. P. (2021) 'Speculating the Past: 3D Reconstruction in Archaeology.' In Champion, E. (ed.) Virtual Heritage. London: Ubiquity Press.

Papadopoulos, C., Gillikin Schoueri, K. and Schreibman, S. (2025) 'And Now What? Three-Dimensional Scholarship and Infrastructures in the Post-Sketchfab Era.' *Heritage. Multidisciplinary Digital Publishing Institute*, 8(3) p. 99.

Schreibman, S. and Papadopoulos, C. (2019) 'Textuality in 3D: three-dimensional (re)constructions as digital scholarly editions.' *International Journal of Digital Humanities*, 1(2) pp. 221–233.

## 278. Hidden in the sands of being FAIR in artificial intelligence in archaeology: the case of the deep learning dataset of qala fortified villages

*Nazarij Bulawka, University of Warsaw*

*Barbara Kaim, Faculty of Archaeology, University of Warsaw*

*Agnieszka Szaforz, Faculty of Archaeology, University of Warsaw*

*Aleksander Kwietniak, Faculty of Archaeology, University of Warsaw*

This poster evaluates the challenges of publishing and developing a deep learning dataset for computer vision, using the example of the "Hidden in the Sand: The Deep Learning Dataset of Fortified Villages (Qala) Project." A qala is a fortified village typically found in Iran, Afghanistan, and surrounding regions, characterised by a rectangular layout, thick walls, and corner towers (Young and Fazeli 2018). These villages were vital for spatial and social organisation during the Islamic period, with preserved examples traceable to the Safavid (1501-1736 AD) and Qajar (1786-1925 AD) dynasties. While relatively recent, qala villages are essential to the archaeology of Central Asia and Iran during the Islamic era, with possible origins dating back to the Bronze Age (Lamberg-Karlovsky 1994). The Hidden in the Sand project is part of a larger effort to create the RADOGOST repository for archaeological data in Poland (DARIAH-PL Consortium). RADOGOST was designed to fill gaps and

address limitations in existing archaeological data repositories, align with ethical and safety standards, and tailor the repository to the needs of Polish archaeology and neighbouring regions. Although geographically distinct, the "Hidden in the Sand" project was integrated into this repository by establishing standards for publishing machine learning datasets.

The project utilised freely available KH-9 HEXAGON imagery, a collection developed during the Cold War (1971-1986) with a spatial resolution of 0.7-1.4 m, accessible through the Earth Explorer platform. KH-9 HEXAGON images are in the public domain, making them an ideal choice due to their license-free status.

This poster will present methods, challenges of development of the dataset and publishing it in the repository, underscores the need for standardised practices for developing deep learning datasets in archaeology.

### References:

Lamberg-Karlovsky, C. C. 1994. 'The Bronze Age Khanates of Central Asia'. *Antiquity* 68: 398–406.

Young, Ruth, and Hassan Fazeli. 2018. 'Landlord Villages of Iran as Examples of Political Economy and Materiality'. *Post-Medieval Archaeology* 52 (1): 34–48. <https://doi.org/10.1080/00794236.2018.1460150>

## 288. Thinking the world. Defensive architectures as landscape builders

*Rodrigo González-Camino, Instituto de Ciencias del Patrimonio (Incipit, CSIC)*

Everything that a society produces is done so in certain ways, encoded in tradition, culture or habit. This goes beyond artifactual productions and involves, among other things, the way in which societies transform the space



they inhabit (Hillier y Hanson 1984). In addition to any other functional or symbolic explanation, the configuration of space and the distribution of elements within it also has a social dimension (Criado-Boado 1993). The Iron Age in the north-west of Iberian Peninsula presents an archaeological reality with great potential to benefit from this kind of observation since, above any other archaeologically recorded materiality, there is the ubiquitous and hegemonic presence of fortified settlements (González-Ruibal 2006). Thus, a monumentalised landscape is presented through constellations of fortified settlements which, in many cases, offer no information beyond their morphology and location.

This work, which is part of a doctoral thesis currently in progress, presents a comprehensive methodology based on geographic information systems and spatial data processing using digital applications to analyse the formation patterns of these settlements. To this end, special emphasis has been placed on the effects of architecture on the perception of the landscape. In addition, a new computational tool is developed to quantify the role of monumental entities in fortified settlements as generators of landscape.

#### References:

Criado-Boado, Felipe. 1993. «Visibilidad e interpretación del registro arqueológico». *Trabajos de Prehistoria* 50 (0): 39-56.  
<https://doi.org/10.3989/tp.1993.v50.i0.488>.

González-Ruibal, Alfredo. 2006. «Galaicos: poder y comunidad en el Noroeste de la Península Ibérica (1200 a.C.-50 d.C.)». *Brigantium Brigantium* (A Coruña) 1: 2006-7.

Hillier, Bill, y Julienne Hanson. 1984. *The Social Logic of Space*. 1.a ed. Cambridge University Press. <https://doi.org/10.1017/CBO9780511597237>

## 291. A Map to Navigate the Data Archipelago: the “Open-archeOcean” Catalogue of Open Datasets for Pacific, Southeast and East Asia Archaeology

*Sebastien Plutniak, CNRS*

### Background

Archaeological datasets are sparsely published and distributed, and efforts to collect and assemble them have been an inherent part of this scientific practice for decades. All along the development of the discipline, multiple calls to openly share structured and reusable data were launched: among others, from Jean-Claude Gardin's 1955 “Problems of Documentation” paper to more recent statements by Charles Perrault in his 2019 “The Quality of the Archaeological Record” book, advocating for the integration of massive datasets to address macro archaeological processes. In this regard, several parts of the globe benefit from large data infrastructures, e.g. “Ariadne” in Europe, “tDAR” in the USA, “ADS” in the United Kingdom, “DANS archaeology” in the Netherlands, etc.

### Subject

This is not yet the case for Pacific, Southeast and East Asia archaeology, where no supranational repository is available. This absence results in higher dispersion of datasets and research efforts, in a region also characterised by its vastness and a manifold of islands, and scarce archaeological investigation; the importance of research carried out by non-local archaeologists and, consequently, particular attention paid to autochthonous data sovereignty (Gupta et al. 2020); and a significant linguistic diversity in publishing.

In this context, “Open-archeOcean” was created, as a curated and interactive online catalogue of open-source datasets for Pacific and Southeast Asia Archaeology (<https://analytics.huma-num.fr/open-archeocsean/>). This catalogue was coined in reference to the European project “OCSEAN. Oceanic and Southeast Asian Navigators” (<https://www.ocsean.eu>) --where its

development started-- a project that aimed at integrating linguistics, genetics, and archaeological data about the long history of human settlement in East and Southeast Asia and the Pacific.

#### Discussion

As an initiative intended for archaeological and local communities, “Open-archeOcsean” is an evolving tool, continuously enriched by monitoring (ancient and recent) resources and open to users' contributions. In this perspective, it draws on the FAIR principles (for scientific data management and stewardship) and CARE principles (for indigenous data governance), implementing them at two levels: 1) about listed resources, by reflecting and highlighting the use of these principles by resources' authors; 2) about “Open-archeOcsean” itself: by publishing its data and code under open licence.

This poster will report on “Open-archeOcsean” current contents, its software infrastructure (based on the “spatialCatalogueViewer” R package), the metadata documented for each listed resource, and some limits of its implementation of the FAIR and CARE principles.

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## 298. Stories from the Ancient Agora in Athens

*Alexandra Katevaini, National and Kapodistrian University of Athens/ American School of Classical Studies at Athens*

Excavation notebooks are first-handing recordings of the excavation usually reserved for study purposes; however, they can be used to narrate the history of the excavation through the people that contributed to the project and formed the archaeological sites as we know them now. The excavations of the Ancient Athenian Agora are a systematic excavation project that started in 1931 by the American School of Classical Studies at Athens. The archaeological site of the Ancient Agora is a central site in the city center of Athens with high numbers of visitors.

The narrative of the Classical Athens is prominent, however there are more stories that exist in the site (Pluciennik 1999). Storytelling is integral to archaeology and its communication with the public (Burlingame and Papmehl-Dufay 2022). This project gives another spin to the source for the stories by using the excavation notebooks and allow the visitors to engage with the site with another lense. As mobile devices are a must have on our everyday life it opens new paths on how to guide the audience engage with the archaeological sites. The tool used to create the stories is the ArcGIS Story Maps application and allow the visitors to engage with the stories via QR codes or statically through a webpage.

The elements of the topic will be technical caveats of using ArcGIS Story Maps and give the participants of the CAA the chance to view the stories. The case study presented is one of the sections of the excavation and works that took place in the area in 1936, 1937, 1950 and 1951.

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## 299. A Coordination Office for Scientific University Collections in Germany

*Louise Tharandt, Humboldt-Universität zu Berlin*

The Coordination Office is a unique institution. It supports and brings together the more than 1300 heterogeneous and versatile collections at universities and colleges in Germany. The Coordination Office promotes the exchange of knowledge, offers advice and assistance, conducts its own research projects, and highlights the importance of the collections to the public. Through its work, it contributes to ensuring that university collections are used in research and teaching and are preserved as cultural and natural heritage.

The Coordination Office maintains a detailed overview of the diverse university collection landscape, from A like Archaeology to Z like Zoology. At the same time, it is a service provider and representative of the interests of the collections. It advises, supports, and networks, for example on issues relating to the storage, preservation, digitization and virtual exhibitions of collections, as well as on ethical issues of collecting. It also publishes central handouts and guidelines for working in and with university collections.

As a research institution, the coordination office is a source of ideas for collection-related issues. It is establishing the data competence center "SODa – Collections, Objects, Data Competences" for scientific university collections, which deals with issues of digitization in collections and data-driven research. A particular concern of the coordination office is the promotion of teaching with collections and objects. To this end, it is involved in the Europe-wide project "Teaching with Objects" and operates the online toolbox for object-based teaching developed in the project.

The coordination office has been in existence since 2012. It was established at the suggestion of the „Wissenschaftsrat“, the most important science policy committee in Germany, with the aim of supporting the further development of university collections in Germany. Internationally, it is regarded as a best practice example of the successful establishment of an overarching institution to support the university collection landscape.

This poster gives an overview of the work the Coordination Office for Scientific University Collections does and the projects it is involved in.

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## 309. Looking at hoards through networks: A new approach to research early medieval depositions in the Middle Dnieper Area

*Inga Utkina-Wöhr, Freie Universität Berlin / Leibniz-Institut für Geschichte und Kultur des östlichen Europa (GWZO)*

Hoards are a very special category of archaeological find. The reasons for the deliberate burial of objects have long been debated in the archaeology of different periods and regions, mostly focusing on a possibility to distinguish between 'profane' and 'ritual' motivations for these actions. Past research has clearly demonstrated the issues connected to this duality of possible motivations (Fontijn 2002, 13–22), as well as to the challenges by interpretation of hoards in general (Bradley 2017). Recent studies have suggested a variety

of theories and methods to gain new insights into this phenomenon, focusing, for example, on the social meaning of space, or the 'biographies' of objects — including their treatment or technological aspects (e.g. Orfanou et al. 2024). Nevertheless, categorizing hoard compositions and depositional contexts is a dominant tool for recognizing different patterns and understanding possible regional or supra-regional dynamics, even though this approach reduces social phenomena. I suggest that a deeper understanding of the complexity of 'hoarding' can only be achieved through a combined quantitative and qualitative investigations. Benefiting from both a quantitative and a qualitative perspectives is possible by using the so-called 'slow' network approach (Deicke 2025). The aim of this poster is to present the theoretical concept that I am working on for my PhD project. This concept enables depositions to be analysed using network analysis, shifting the focus from motivation to modelling the interactions of responsible communities and social groups.

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metalworking and hoarding in Bronze Age societies.” *Sci Rep* 14: 16153.  
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## 314. Towards a Comprehensive Virtual Landscape of the Funnel Beaker Culture

*Pawel Bernaciak, The University of Edinburgh*

The Funnel Beaker Culture (TRB) of North-Central Europe (c. 4000–2800 BCE) is characterized by its megalithic tombs and clustered settlements. Despite decades of research, knowledge of TRB landscapes remains fragmented. Most studies have focused on local groups (e.g. Kuyavia, West Pomerania, or the recently identified Świętokrzyskie cluster in Poland), while the culture's full geographic range extends from Poland through northern Germany to Denmark. This localized focus has limited our understanding of TRB's broader cultural and environmental dynamics.

To address this gap, our project proposes a unified digital framework for reconstructing the TRB cultural landscape at a pan-regional scale. We integrate multi-regional archaeological datasets with GIS-based spatial analysis and paleoenvironmental data to build an interactive digital model of TRB settlements and monument sites. Methodologically, the project combines remote sensing inputs (LiDAR, aerial imagery) and geophysical survey data to map funerary monuments and settlements across diverse terrains. Early findings from case studies in Kuyavia and West Pomerania reveal non-random patterns – for instance, TRB megalithic tombs often occupy elevated areas near water sources, underlining the influence of topography and resources on site selection.

Moving beyond static maps, the envisioned model enables dynamic simulations of Neolithic lifeways. For example, we are analyzing the potential migratory spread of early farming communities, modelling socio-economic interaction networks among TRB populations, and assessing their ecological impacts on the landscape (e.g. patterns of deforestation or soil usage). This

simulation capability allows us to explore how TRB communities might have interacted with and transformed their environment, providing insights into socio-environmental feedbacks over time.

This holistic approach aims to bridge the gaps between isolated regional studies by standardizing and integrating data into a single computational framework. The poster will present the project's conceptual design, methodology, and preliminary results, demonstrating how advanced digital tools can unite localized studies into a pan-regional perspective. In doing so, we seek to contextualize TRB's role within the broader Neolithic transformations of Europe, illustrating the value of comprehensive landscape modelling in archaeological research.

Key words: Funnel Beaker Culture; Neolithic; GIS; spatial analysis; cultural landscape; megalithic tombs

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### 317. Recreating, Creating, or Imagining: Building a Digital Model of a Danish Hypocaust Based on Photogrammetry and Laser Scanning

*Morten Birk Jørgensen, The Royal Danish Academy*

*Mads Lou Bendtsen, Aarhus University*

*Thomas Hacksen Kampmann, The Royal Danish Academy*

This project focuses on the design of a digital model as the basis for the construction of an anastylosis of a medieval hypocaust, excavated in 2025 at Hjortespring, Herlev Municipality, Denmark. The excavation involved the systematic dismantling of the structure's stones and bricks, accompanied by continuous photogrammetric documentation and laser scanning of each course in the brickwork. Using the collected data, this study explores multiple approaches to digitally reconstruct the hypocaust, integrating photogrammetry, laser scans, and comparative research on similar archaeological finds.

While the term "hypocaust" is commonly associated with the radiant heating systems of ancient Greek temples and Roman baths, a distinct medieval variant emerged in Northern Europe and the Baltic region. Unlike their ancient counterparts, which relied on radiant heat from floors and walls, these medieval systems utilized convection heating. Air was channeled through a combustion chamber, heated a bed of natural stones, and circulated directly into the interior once the fire subsided (Tvauri 2009, 71-72).

Hjortespring is a suburb of Copenhagen within Herlev Municipality and the find site is situated adjacent to a local art museum, a retail center, and residential areas. During preparatory work for a new housing development, a local developer uncovered evidence of a medieval hypocaust—a feature typically associated with high-status settlements. Kroppedal Museum, responsible for archaeological oversight in the area, conducted a comprehensive excavation. Combined with historical sources, the excavation revealed a royal hunting estate established by Frederik II around AD 1586, with the

hypocaust likely serving as the primary heating system for the building (Bizoev 2024).

Following the excavation by Kroppedal Museum, the site was released for development. However, the developer expressed a desire to preserve the site's historical significance by constructing an anastylosis of the hypocaust. To support this intention, the authors of this paper participated in a subsequent dismantling of the structure and developed a digital model to serve as the foundation for its physical reconstruction.

The preservation of cultural heritage landmarks raises critical questions: Should the hypocaust be preserved in its current state, reconstructed, or restored to a functional condition? How should an isolated structure, devoid of its original building, flooring, and intangible elements—such as heat, light, and scent—be interpreted? This poster addresses these challenges, alongside issues related to digital documentation and reconstruction methods.

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### 343. R–Python workflow for unsupervised classification of artefacts using Conventional Mixture of Experts

*Anastasiia Korokhina, Leibniz-Institute for the History and Culture of Eastern Europe*

The search for optimal automated procedures for object classification remains one of the key challenges in data preparation and analysis within archaeological research. In many contexts, unsupervised classification from an

etic perspective is the only viable way to approach a genuine typology of artefacts.

This work presents a lightweight and original workflow for unsupervised classification of archaeological finds based on two-dimensional images (archaeological drawings). The workflow includes the following stages: semi-automatic image processing, morphometric description using elliptic Fourier coefficients (Kuhl & Giardina 1982), and the classification step implemented via a Mixture of Experts (MoE) model (Jacobs et al. 1991).

The Mixture of Experts approach combines a gating network, which partitions the feature space, with a set of local expert models that capture data structure within each partition. In this workflow, the gating network is represented by a Self-Organizing Map (SOM), while each expert is implemented as a Gaussian Mixture Model (GMM) trained on the data assigned to its SOM node.

Several experimental variants of the procedure were tested:

- (1) Explicitly localised experts — data were pre-processed by the SOM, and each expert was trained on a separate node, collectively covering the entire observation space;
- (2) Implicitly localised experts, where the SOM-based gating and the experts were trained jointly on the full dataset;
- (3) Implicitly localised experts with Bayesian priors derived from the mixture of explicitly localised expert results.

Additionally, the influence of feature-space reduction to meta-features and their subsequent ranking using mutual information was evaluated. Based on visual and statistical assessment, the first variant (mixture of explicitly localised experts) demonstrated the most interpretable and stable classification outcomes.

The procedure was tested on Middle Neolithic material from the North Central European Lowlands (Lorenz 2018). It can be extended to any type of archaeological objects and contributes to the development of unsupervised classification methods.



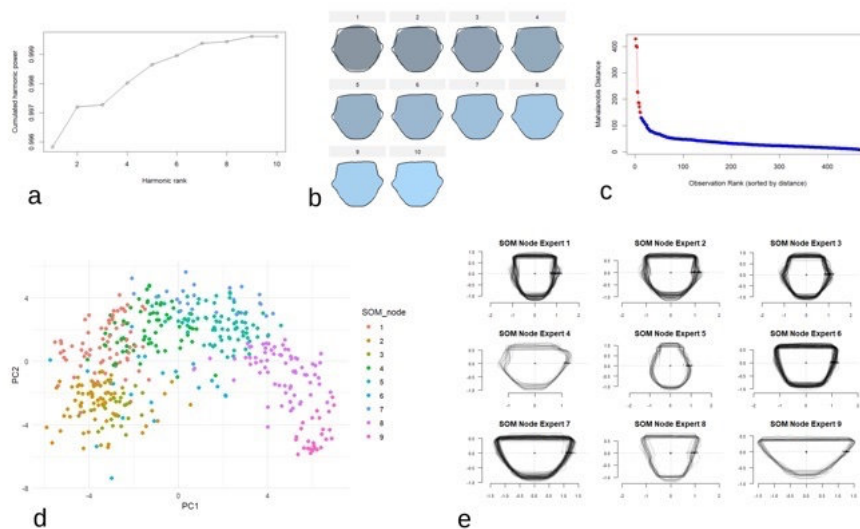


Fig. Main stages of pottery form classification using the Mixture of Experts (MoE): a – Plot of harmonic power used to describe vessel outlines; b – Reconstruction of a randomly selected vessel outline using elliptic Fourier coefficients; c – Detection of multivariate outliers; d – Trained experts visualized in a 2D principal component space; e – Preliminary classification of outlines using the MoE (all plots were generated in R)

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## 385. In the footsteps of travellers – an analysis of the course of old communication routes in the Low Beskids

Weronika Wnuk-Ciastek, University of Warsaw

Jerzy Ciastek, University of Warsaw

The Low Beskids region has almost always formed the southern border of Poland. In our research, as part of the reconstruction of selected elements of the cultural landscape of this area, we have attempted to recreate as accurately as possible the network of communication routes and defensive structures (including hillforts) in the Middle Ages. The course of communication routes and the location of hillfort were determined on the basis of written sources, the location of defensive positions (data from the Polish National Heritage Institute; Marszałek 1993) and the terrain (assuming no significant changes to date). An attempt was also made to locate strongholds in the Low Beskids, whose location was previously unknown but which were mentioned in historical sources. Using a digital terrain model and vegetation indicators, at least one previously unknown stronghold was located. The DTM was illuminated at an angle of 45 degrees from 8 directions (N, NE, E, SE, S, SW, W, NW) to minimise the risk that shadows or light from a specific direction would obscure smaller landforms or depressions (Banaszek 2015). The spatial resolution of the data is 1 m. The analysis also included colour compositions of images in near-natural colours and CIR, as well as the calculation of vegetation indices such as NDVI (Normalised Difference Vegetation Index). All analyses were performed using QGIS software.

Local changes in vegetation are very helpful in searching for archaeological sites or their traces in ploughed fields, but it is difficult to search for smaller sites in forested areas. However, the Digital Terrain Model is effective both in fields and forests, allowing the discovery of previously unknown sites without the need for long field expeditions. Indicating the specific coordinates of the sites found allows for short field trips to specific locations for verification, instead of tedious searching of the area metre by metre. Research using remote sensing techniques is not new, especially the use of DTM in scientific

research in Europe and worldwide (Kucukkaya 2004, 83-88), but this is the first attempt to use DTM and vegetation indices to reconstruct a network of communication routes and defensive sites in the area in question.

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### 389. Linking Analytical Data through Semantics: Challenges and Perspectives in Archaeometric Research

*Lorena Bravi, Sapienza University of Rome*

*Martina Naso, Sapienza University of Rome*

*Massimiliano Puntin, Sapienza University of Rome*

#### Subject

The proposed study presents a methodological framework for the semantic mapping of archaeometric data, starting from X-Ray Fluorescence (XRF) analytical processes on archaeological ceramics. The approach is grounded in ontological and graph-based modelling, which allows the explicit representation of relationships between samples, instruments, parameters, and interpretative results. By describing each analytical steps (Johnson et al. 2024): data acquisition, calibration, quantification, and interpretation as an interconnected set of entities and events. The model aims to preserve contextual information while supporting a more structured and interoperable

representation of analytical data. The workflow combines controlled vocabularies, persistent identifiers, and open metadata standards (e.g., CIDOC CRM, CRMsci, CRMarchaeo) to enhance data transparency and reproducibility (Bekiari et al. 2024).

#### Background

In archaeometric research, data heterogeneity remains one of the major challenge to the integration and reuse of scientific information. Analytical results often differ in structure, units, precision, and terminology, depending on the instrument, calibration protocol, and research purpose. This fragmentation hampers the comparison and interoperability of datasets, limiting the potential for large-scale, cross-contextual interpretations. Also, the lack of shared reference vocabularies and standardised recording schemes makes it difficult to trace, validate, and compare results across laboratories and projects.

#### Discussion

This semantic strategy has broader implications for the adoption of computer applications and quantitative methods in archaeology. By linking archaeometric data through shared ontologies, it becomes possible to bridge the gap between laboratory-based analyses and archaeological interpretation, thus promoting data comparability and reuse across institutions and research domains. Moreover, by incorporating calibration information within the data structure, the model encourages a more transparent and consistent assessment of analytical reliability. While the current implementation focuses on ceramic materials analysed through XRF, the modular nature of the framework ensures scalability to other techniques (e.g., FTIR, Raman, XRD) and material classes (e.g. litics, metals). In the long term, the goal is to contribute to a unified digital ecosystem where archaeometric datasets are no longer isolated outputs but interoperable components of a broader knowledge infrastructure for cultural heritage research.

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### 396. XRONOS: An open data infrastructure for archaeological chronology

*Joe Roe, University of Copenhagen*

*Martin Hinz, Kiel University*

Computational archaeologists have benefited immensely from our field’s embrace of open data and open science approaches. One of the principle domains in which this has been applied in recent years is chronometric data. Comprehensive compilations of radiocarbon dates have become available for many parts of the world in the last decade and, as natural next step, there are now several initiatives to collate this data globally, including the retrieval tool c14bazAAR (Schmid, Seidensticker, and Hinz 2019), the IntChron exchange format (Bronk Ramsey et al. 2019), and the synthetic database p3kc14 (Bird et al. 2022). But this effort is far from complete. Radiocarbon datasets are still sorely lacking for many parts of the world and, even in those regions with good coverage, the quality of data is highly uneven and largely undocumented. There exists no central repository ensuring the long-term sustainability and completeness of these datasets, and the potential of placing other sources of chronometric information (e.g. dendrochronology, typological dating) in an open data framework has hardly been realised at all.

Here, building on and complementing these initiatives, we present XRONOS (Roe et al. 2025, <https://xronos.ch>), an open data infrastructure for archaeological chronology. It provides open access to published radiocarbon dates and other chronometric data from any period, anywhere in the world. By collating a large number of existing regional and global compilations of dates, XRONOS offers the most comprehensive radiocarbon database yet published, with over 350,000 radiocarbon and 75,000 site records. It also provides a foundation for expanding the systematic collection of chronometric information beyond radiocarbon, with support for typological and dendrochronological dates and a generalisable data model that can be adapted to other methods of absolute dating. Automated and semi-automated quality control processes ensure that data from diverse sources is continuously integrated and standardised, making it easier to find information of interest and reducing the need for manual data cleaning by end users. The XRONOS framework provides more open, more reliable, and more comprehensive access to chronometric data than previously available, that has already helped further the application of quantitative and computational methods in archaeological chronology.

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## 411. archaeo.social and archaeo.dev: decentralised, collective digital infrastructure for archaeologists

*Joe Roe, University of Copenhagen*

*Zachary Batist, McGill University*

*James A. Fellows Yates, Max Planck Institute for Evolutionary Anthropology*

*Andrea Titolo, University of Turin*

In November 2022, the microblogging service Twitter (now X) was acquired by billionaire Elon Musk, triggering the first of several exoduses of its users. Amongst those who left the site for other platforms, or who simply stopped using it, were archaeologists and other scientists. ‘Science Twitter’ had been a prominent venue for scholarly communication on social media, providing a platform for researchers to talk directly to each other and to the public (Insall 2023). Its sudden disintegration was a wake-up call for many, highlighting the risks of entrusting public scientific discourse to a single private corporation. Subsequent events have only reinforced academia’s need for digital services that are resilient to corporate capture, ‘enshittification’, and data colonialism (Brembs et al. 2023). And yet much of the digital infrastructure we rely upon as archaeologists—not just in terms of social media and communication, but software development, code sharing, collaboration, and so on—remains concentrated with a few large corporations.

archaeo.dev (<https://archaeo.dev>) is a scholarly collective that maintains decentralised digital services for archaeologists. We use free and open source software to promote a ‘do it yourself’ approach to digital research and

scholarly communication tools, with the aim of breaking our field’s dependence on centralised, proprietary platforms. The collective began in 2022 with archaeo.social (<https://archaeo.social>), a federated social media platform created in response to the ‘scientific exodus’ from Twitter. Since then, we have built on the model with other decentralised services, including instant messaging platform Matrix (<https://chat.archaeo.social>), software development platform Forgejo (<https://forge.archaeo.dev>), and collaborative text editor HedgeDoc (<https://md.archaeo.dev>). These are used by and supported by hundreds of individual users and a number of scholarly societies. Though ‘free as in freedom’, maintaining these services does require an investment in money, time, labour, and skills in system administration – creating a significant barrier to entry for individual scholars. The aim of archaeo.dev is to overcome this barrier by pooling our resources and operating these tools collectively. With this poster, we invite members of the CAA community both to use them, and help us build them further.

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## 424. Generative Artificial Intelligence to simulate ancient environmental landscapes

*Elisa Paperini, University of Pisa*

Reconstructing past landscapes is a key task in archaeology for understanding how human societies interacted with their environments. Traditionally, this work has relied on proxies such as pollen, charcoal, and isotopic data. The recent development of Generative Artificial Intelligence (GenAI) opens new possibilities for visualizing palaeoenvironments, offering realistic outputs that can support both research and public dissemination. Yet, their use raises methodological and epistemological questions: to what extent can GenAI-generated images be considered scientifically valid representations of the past?

#### Subject

This poster presents an experimental workflow that integrates predictive and generative AI components to reconstruct vegetational landscapes from diachronic pollen data. In the predictive phase, a Random Forest model trained on 41,831 European pollen records (Holocene to present) estimates the dominant biome for each sample. In the generative phase, a multimodal GenAI system (based on Stable Diffusion) translates these biome predictions and site metadata into visual outputs depicting the likely vegetation structure. Archaeological and palaeoecological expertise is used to evaluate the accuracy and plausibility of the generated images.

#### Discussion

The study discusses both the scientific and communicative potential of GenAI in environmental archaeology. On one hand, generative models can produce engaging, contextually informed images that help visualize and communicate complex datasets. On the other, they challenge traditional notions of evidence, as their apparent realism may obscure the uncertainty underlying palaeoenvironmental reconstruction. By critically comparing generated landscapes with expert assessments and palaeoecological expectations, this research explores how GenAI can complement, rather than replace, human interpretation. Ultimately, this work argues for a reflective integration of generative AI into archaeological practice, emphasizing transparency,

evaluation protocols, and collaboration between computational and domain experts.

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## 425. Integrating magnetometry and ground penetrating radar at the American Revolutionary War fortification in Butts Hill Fort (Portsmouth, Rhode Island, USA)

*Samuel Koontz, University of Kentucky*

*Alexander Wise, Department of Computer Science, University of Kentucky*

*Ryan Nolin, Department of Mechanical and Aerospace Engineering, University of Kentucky*

*James Keppeler, Department of Anthropology, University of Kentucky*

*Marcus Rodriguez, William S. Webb Museum of Anthropology*

*Philip Mink, William S. Webb Museum of Anthropology*

*George Crothers, William S. Webb Museum of Anthropology*

*Paul Murphy, Battle of Rhode Island Association, Portsmouth*

*John Robertson, United States Military Academy, West Point*

*Alexandra Uhl, Department of Sociology and Anthropology, Stonehill College*

*Sean Bailey, Department of Mechanical and Aerospace Engineering, University of Kentucky*

*Hugo Reyes-Centeno, Department of Anthropology, University of Kentucky*

The Battle of Rhode Island in 1778 stands as a critical yet understudied episode in the American Revolutionary War. The conflict between the newly allied American and French military against the British-Hessian forces culminated at Butts Hill Fort in Portsmouth, Rhode Island, United States. Historic accounts show that the fort once contained barracks, battery, and magazine structures within rising earthwork fortifications, with only the earthworks visible today. A previous remote sensing survey found evidence that buried components of the barracks structure remain underground today (Keppeler, 2025); however, additional multi-modal research was recommended to verify the presence of the barracks and the other buried structures. Integrating

multiple remote sensing methods allows for imaging of multi-layer maps and strengthens confidence in feature-identification (Conyers, 2017; Samadzadeh, 2025). Therefore, this research combines additional remote sensing techniques to investigate the presence or absence of subterranean architectural features within the fort. In this study, publicly available satellite and LiDAR data was used in conjunction with original ground penetrating radar (GPR) and magnetometry data to create digital maps and 3D interpolations of the subterrain. A GPR survey was implemented utilizing a stepped-frequency radar Kontur GROUND 1212 system (30 – 4,000 MHz) in combination with a pulsed radar MALÅ RAMAC GPR CU II (500 MHz) system and a SENSYS multichannel magnetometer, combined with a SPECTRA Precision Global Positioning System (GPS). The surveys were conducted across the area within the earthworks, along with select areas outside the fortification at 0.25 and 0.50 cm transects in select areas, targeting the locations of each architectural feature. Our GPR data results revealed a cluster of rectilinear anomalies at a depth of roughly 18-55 cm where the barracks building once stood. Magnetometry data revealed additional localized anomalies in the same area, with partial overlap with the GPR features, indicating a geophysical correspondence between the two datasets (Figure 1). Several isolated magnetic anomalies are also distributed across the broader survey area, unrelated to the primary architectural pattern. The results of these surveys suggest that components of the barracks building are still present underground and align with the locations of architectural features indicated on historical maps, confirming previous results; however, little evidence for remains of the battery and magazine structures was detected and the provenance of the other anomalies is currently unclear. These findings provide insight into the site's spatial composition, informing discussions about the preservation and management of this historical archaeology site, as well as the limitations of relying on historical maps to infer site formation processes.



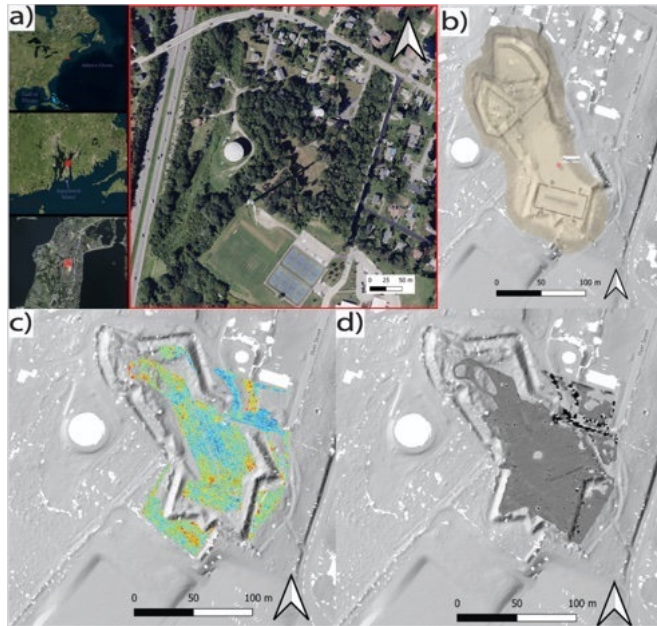


Fig. Maps of Butts Hill Fort with a series of overlays. (a) Sattelite images of Aquidneck Island and Butts Hill Fort. (b) Publically available LiDAR map overlaid with a modified portion of the 1777 Clinton Plan Nr. 19 map, depicting barracks, magazine, and battery structures. (c) LiDAR map overlaid with ground penetrating radar results at a depth of 18.5 cm. Red areas represent higher amplitude signals. (d) LiDAR map overlaid with magnetometry data. Black features represent a positive magnetic (nT) value, white features represent a negative magnetic value.

#### 445. Inked in 3D: Surface modelling and image enhancement of a tattooed human mummified individual from Benguet, Philippines

*James Keppeler, University of Kentucky*

*Dominik Göldner, DFG Center for Advanced Studies "Words, Bones, Genes, Tools,"*

*Cindy Copas, Office of the Indigenous Peoples Mandatory Representative (IPMR 2017-2021)*

*Sario Copas, Office of the Indigenous Peoples Mandatory Representative (IPMR 2017-2021)*

*Rita Peyroteo-Stjerna, University of Uppsala*

*Max Larena, University of Uppsala*

*Hugo Reyes-Centeno, University of Kentucky*

Decorative tattoos preserved on human mummified remains have been documented globally for at least 5,000 years (Friedman et al. 2018) and can serve as a symbolic archive of socio-cultural narratives, as well as a source for understanding cross-regional ethno-linguistic connections. Southeast Asia has a ~10,000-year tradition of mummification (Hung et al. 2025); however preservation of soft tissue that could retain tattoo symbols is rare due to the predominantly warm, tropical environments of the region. In addition, limited conservation strategies in the face of climate change and increasing international tourism further threaten the preservation of tattooed mummified remains; thus, their documentation is an essential part of heritage management strategies. This work therefore presents a case study applying three-dimensional photogrammetry and decorrelation stretch techniques to document the elaborately tattooed and mummified remains of Apo Anno, an individual revered in the Benguet Province of the Northern Philippine Island of Luzon. First, we collected 1,849 images of Apo Anno using traditional photography and structured light scanning, and used these within a

structure-from-motion photogrammetry workflow to generate a three-dimensional (3D) model made up of 105 million polygons. Then, we applied the decorrelation stretch algorithm based on the multivariate Karhunen-Loève transformation using DStretch (Harman 2005), which digitally enhances levels of contrast between similar color values in an image. While most previous applications of DStretch have been made to single images, our approach was to apply the algorithm to the color texture file of Apo Anno in order to enhance the visibility of faded tattoos in 3D. Results featured a high-quality 3D rendering of Apo Anno that contrast his tattoos with the surrounding mummified skin, allowing for a more complete visualization than traditional imaging, particularly in areas where tattoos have begun to fade or deteriorate (Figure 1). We identify examples of tattoo motifs in Apo Anno that can be compared to other conserved mummified examples and material symbols in the Philippines, as well as other parts of Southeast Asia and the Pacific. The results of this study, alongside newly obtained genomic and radiometric chronological data, contextualize Apo Anno within pre-Hispanic mummification and tattooing practices in the Northern Philippines. The joint application of documentation and analytical methodologies in this case study serves as a model for the future documentation of other tattooed mummified individuals.

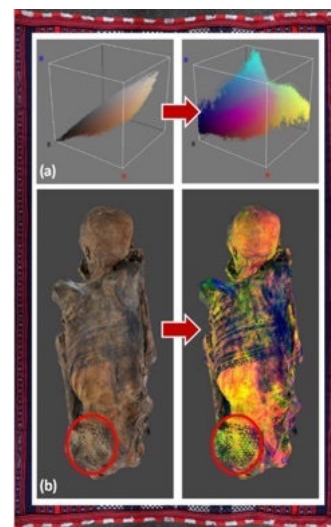


Fig. Apo Anno mummified individual from Benguet, Philippines: (a) Color graph of the Apo Anno texture file in three dimensions before and after the application of decorrelation stretch, followed by (b) the texture file wrapped on the 3D model of Apo Anno (dorsal view) before and after decorrelation stretch. Note enhanced representation in left pelvic region (red circle). Images are overlaid on a traditional death blanket.

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## Wednesday

### S2: Our Little Minions pt. VII: Small Tools with Major Impact

*Brigit Danthine, Austrian Archaeological Institute (Austrian Academy of Science), Vienna, Austria*

*Ronald Visser, Saxion University of Applied Sciences, Deventer, Netherlands*

*Florian Thiery, Research Squirrel Engineers Network, Mainz, Germany*

**Location:** Franz König Saal

**Session Format:** Other

*This seventh Little Minion session invites short presentations, lightning talks (max. 7-10 minutes, including very brief discussion), of small coding pieces, software, or hardware solutions at any stage of completion, not only focusing on fieldwork or excavation technology, associated evaluation, or methodical approaches in archaeology. Each talk should explain the innovative character and mode of operation of the digital tool. The only restriction is that the software, source code, and/or building instructions must be open and freely available.*

*After the previous year's spontaneous success of "Stand-up-Science", you will also have the opportunity to spontaneously participate and demonstrate what you have on your stick or laptop. If you would like to participate without submitting an abstract in the spontaneous section of the session, please don't hesitate. Please come and spontaneously introduce your little minion!*

In our daily work, small, self-made scripts (e.g., Python or R), home-grown small applications (e.g., QGIS Plugins), and small hardware devices significantly help us get work done. These little helpers ("little minions") often reduce our workload or optimise our workflows, although they are not often presented to the outside world and the research community [1]. Instead, we generally focus on presenting the results of our research and use our small tools silently during the process, without even pointing to them, especially not to the source code or building instructions. This session will focus on these "little minions", and we invite researchers to share their tools so that the scientific community may benefit. As we have seen in last year's "minion talks" since 2018, there is a wide range of tools to be shared. The Little Minion software tools have evolved from their niche existence into essential components of projects and consortia. They are a significant part of the archaeological Research Software Engineering community (also known as Computational Archaeology) and play a crucial role in the Research Data Management (RDM) process within the Research Data Lifecycle and the digital object biography [2]. This can result in, for example, FAIRification Tools [3-4] and research tools for reproducible quantitative/spatial analysis used in international and interdisciplinary initiatives, such as the German National Research Data Infrastructure (NFDI) [5-7], the European Collaborative Cloud for Cultural Heritage (ECCCH), or ARIADNEplus.

This seventh Little Minion session invites short presentations, lightning talks (max. 7-10 minutes, including very brief discussion), of small coding pieces, software, or hardware solutions at any stage of completion, not only focusing on fieldwork or excavation technology, associated evaluation, or

methodical approaches in archaeology. Each talk should explain the innovative character and mode of operation of the digital tool. The only restriction is that the software, source code, and/or building instructions must be open and freely available. Proprietary products cannot be presented, but open and freely available tools are designed for them. To support the subsequent use of the tools, the goal should be to make them open and available to the scientific community (e.g., GitHub, GitLab).

We invite speakers to submit a short abstract, including an introduction to the research tool, a link to the repository (if possible), access to the source code, and an explanation of which group of researchers could benefit from the tool and how. The tools may address the following issues, but are not limited to:

- data processing tools and algorithms
- measuring tools
- digital documentation tools
- GIS plugins
- hands-on digital inventions
- data-driven tools

After the previous year's spontaneous success of "Stand-up-Science", you will also have the opportunity to spontaneously participate and demonstrate what you have on your stick or laptop. If you would like to participate without submitting an abstract in the spontaneous section of the session, please don't hesitate. Please come and spontaneously introduce your little minion!

The Minion session is designed for interested researchers from all domains who want to present their small minions, with a focus on the technical domain, as well as for researchers who wish to explore the types of little minions available to help with their own research questions. We all use minions in our daily work, and often, tools for the same task are built multiple times. This online session provides a platform for tools that are usually considered

too unimportant to be presented in traditional talks, but are crucial and extensive steps in our research.

As a result of the session, we aim to provide support, ensuring that all the presented tools and links to code repositories are available to the research community on our website <https://littleminions.link>.

A sub-group of the CAA SIG Scientific Scripting Languages in Archaeology (SSLA), the "little minions", organises this session. The core aim of this SIG is to focus on the application of Scripting Languages in archaeological research.

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**16:00 –  
19:30**

**Individual  
breaks**

- 1. Detecting Temporal Relations in Archaeology: Model and Algorithms  
*Eythan Levy (University of Zurich)*
- 3. From Clay to Code: A Digital Solution for Annotating Cuneiform Texts  
*Laura Schimmelfennig (Ruprecht-Karls-Universität Heidelberg)*
- 46. chublets.software – From hidden Little Minions to an Archaeological Research Software Marketplace  
*Florian Thiery (LEIZA); Lutz K. Schubert (University of Cologne)*
- 47. SPARQLing Unicorn Research Toolkit – Little Minions for FAIR Archaeological Data  
*Florian Thiery (LEIZA); Fiona Schenk (Johannes Gutenberg University Mainz); Daria Stefan (TU Wien)*
- 135. Web scrapping of an archaeological dataset using Python: An ADS bifaces dataset example  
*Juan Palomeque-Gonzalez (IDEA- Madrid)*

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- 223. Wikidata Meets QGIS: Enhancing Archaeological Interpretation with Visual Foundation Models  
*Jürgen Landauer (Landauer AI); Florian Thiery (LEIZA)*
  - 238. Secanto - Recent developments  
*Vincent Mom (DPP)*
  - 273. TagLab - a semantic segmentation tool. Now, also for CH  
*Marco Callieri\*; Gaia Pavoni\*; Massimiliano Corsini\*; Federico Ponchio\*; Alessandro Muntoni\*; Paolo Cignoni\**  
  
*\* ISTI-CNR*
  - 281. QSKOS. Development of a plugin for integrating controlled vocabularies into QGIS  
*Lasse Mempel-Länger\*; Anja Cramer\*; Benjamin Streubel\*; Kristina Fischer\*; Florian Thiery\*; Ingrid Stelzner\*; Nico Wende\*; Allard Mees\**  
  
*\* LEIZA*
  - 282. The "QSaurus". A QGIS-Plugin to implement (SKOS) Thesauri into QGIS  
*Brigit Danthine (Austrian Archaeological Institute); Sinan Zülfikar (Austrian Archaeological Institute)*
  - 395. MergeLines: a tool to merge adjoining linear structures based on contiguity angles  
*Nathanaël Le Voguer (UMR 7324 CITERES-LAT*
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- 416. STON: a practical imaging tool for archaeological petrography and beyond  
*Evgenia Dammer (Rathgen Research Laboratory); Romain Thomas (University of Sheffield)*
  - 444. Digging for Answers: Unearth the Most Suitable Machine Learning Model  
*Daria Stefan (TU Wien); Iris Grze (TU Wien)*
  - 446. Data driven landscape reconstruction for Blender Software  
*Marti Košťál (Masaryk University)*
- 

## 1. Detecting Temporal Relations in Archaeology: Model and Algorithms

*Eythan Levy (University of Zurich)*

### Introduction

Temporal relations are mathematical objects expressing how two time-periods (a.k.a. time-intervals) relate to each other chronologically. Since archaeology is strongly involved with the study of time and its representation, temporal relations are naturally relevant in this field. The best-known formal system of temporal relations is that of James Allen (Allen 1983; Allen 1984) which, though not originally designed for archaeology, is often quoted in archaeological literature. In Levy 2025, we argued that archaeology necessitates an alternative, more complex, system of temporal relations, and presented such a system in detail, inspired by the set of relations available in the ChronoLog tool for chronological modelling (<https://chrono.ulb.be/>; Levy et al. 2021). The proposed paper builds on this system by exploring the full

structure of implications between the temporal relations. Using this structure, four algorithms are presented to compute the strongest possible temporal relation between two time-periods, even in the presence of uncertainties regarding their boundaries.

### Results

The paper presents four different algorithms for detecting the strongest possible temporal relation between two time-periods with known, unknown or approximated boundaries. These algorithms are based on classical algorithmic methods, such as topological sorting, depth-first graph search, and tree traversals. Our results are described in detail in a preprint available on HAL (<https://hal.science/hal-05210722v1>). An open-source Python implementation of our time-period data structure and of the four algorithms is available on GitHub (<https://github.com/Eythan31/Temporal-relations>).

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<https://doi.org/10.1111/arcm.13080>.



### 3. From Clay to Code: A Digital Solution for Annotating Cuneiform Texts

*Laura Schimmelfennig (Ruprecht-Karls-Universität Heidelberg)*

#### Introduction:

The study of cuneiform inscriptions represents one of the most central tasks in Near Eastern Archaeology and Assyriology. These texts provide unparalleled insights into the cultural, political, and economic life of ancient Mesopotamia, yet their scholarly treatment remains both time- and labor-intensive. The processes of transliteration, annotation, and digital preparation of inscriptions often involve a patchwork of analog sign lists, heterogeneous digital databases, and manual formatting conventions for publication that hinder efficient scholarly workflows. In recent years, the proliferation of digital projects such as the Cuneiform Digital Library Initiative (CDLI) and the Open Richly Annotated Cuneiform Corpus (ORACC) has greatly expanded the availability of digitized inscriptions.

However, the lack of consistent formatting standards, the uneven integration of transliterations, and the fragmentation of resources remain significant barriers to research. At the same time, advances in computational methods - particularly optical character recognition (OCR) and Natural Language Processing (NLP) - have raised expectations for more automated solutions (Sahala et al. 2020, Stötzner et al. 2023, Gordin et al. 2024). Yet the successful application of such methods remains constrained by the insufficient accessibility of large standardized corpora. Against this background, there is an urgent need for pragmatic tools that both meet immediate scholarly requirements and pave the way toward more robust computational analysis.

#### Methods and Materials:

This paper introduces CUNEINOTATE, a digital application developed to streamline the process of cuneiform annotation and transliteration by directly linking image-based data with export-ready digital formats. Written in

Python using the PyQt framework, CUNEINOTATE combines a user-friendly graphical interface with robust backend functionality. At its core, the tool integrates two newly developed preliminary databases:

1. The Single Sign Dictionary (SSD). This dataset consolidates sign lists from ORACC, the Electronic Babylonian Library (eBL), and Borger's Assyrisch-Babylonische Zeichenliste (1981), covering nearly 1000 unique cuneiform characters. Each entry is represented in Unicode and linked to corresponding transliterations and Borger numbers. The dataset is stored in a JSON format for easy access and extensibility. Ambiguous signs are represented as multi-entry lists, allowing users to retain interpretative flexibility during annotation. The Borger numbers ensure swift look ups in analog sources.

2. The Radical Search Dictionary (RSD). This newly designed database enables the identification of unfamiliar signs by decomposing them into their constituent radicals - vertical strokes, horizontal strokes, diagonal strokes, and wedges (Winkelhaken). Users can count visible radicals on an inscription and query the database to locate the most likely sign candidates, even when no prior identification is available. The RSD is further subdivided into chronological and regional variants (Neo-Assyrian, Neo-Babylonian, Old-Babylonian Cursive, Old-Babylonian Monumental, and Hittite), thus supporting a historically sensitive approach to sign recognition.

To ensure interoperability, the tool implements an automated conversion into the ASCII Transliteration Format (ATF) used by ORACC and CDLI to publish transliterations. This ensures that annotated texts can be seamlessly integrated into existing corpora. The application also provides customizable input mechanisms, including escape-sequence mapping to specialized Unicode characters, enabling efficient and flexible transliteration across different keyboard setups.

#### Results:

CUNEINOTATE provides several significant improvements over existing workflows. By automating ATF conversion and formatting, the tool eliminates one of the most repetitive and error-prone aspects of transliteration. The radical search functionality reduces dependence on expert-level familiarity with sign lists, thereby lowering the entry barrier for students and early-stage researchers. Additionally, ambiguities in sign readings are preserved and clearly documented, ensuring that scholarly uncertainty is not lost in digital conversion.

Also, cross-referencing with Borger's numbering system allows for rapid navigation between digital and analog resources, making the tool valuable in both research and pedagogical contexts. The platform centralizes multiple resources into a single interface, replacing the need for fragmented workflows involving multiple databases, sign lists, and formatting tools.

Preliminary testing has demonstrated that CUNEINOTATE can reduce transliteration time significantly, while simultaneously producing standardized, publication-ready outputs that conform to ORACC and CDLI requirements.

#### Discussion:

Beyond immediate gains in efficiency and usability, CUNEINOTATE carries broader implications for the future of digital Assyriology. By contributing standardized and well-structured outputs, the tool directly addresses one of the major obstacles to applying computational and especially machine learning (ML) techniques to cuneiform data: the lack of sufficiently large, reliable, and consistent digital data. While current ML applications have shown promise in specific domains such as OCR-based sign recognition or neural machine translation of Akkadian texts, they remain limited by dataset quality and scope. Tools such as CUNEINOTATE thus provide a crucial bridge, supporting both traditional scholarship and computational experimentation.

Moreover, the integration of radical search functionalities introduces a methodological alternative to purely ML-driven approaches. Rather than requiring extensive training data, the radical-based method leverages the intrinsic structure of cuneiform writing to facilitate sign identification, thus

offering a low-resource solution that complements ongoing computational efforts.

The application also highlights the importance of adaptability in digital scholarship. As new sign lists, transliteration conventions, and corpora become available, the JSON-based architecture allows for straightforward updates and extensions. In this sense, CUNEINOTATE is not only a tool but also a framework that can evolve in tandem with the field.

#### Conclusion:

CUNEINOTATE represents a pragmatic, open-access contribution to the digital humanities and computational archaeology. By addressing pressing challenges in efficiency, standardization, and accessibility, it provides immediate value for Assyriologists and Archaeologists while also contributing to the long-term goal of creating robust digital corpora for advanced computational analysis. Future developments may include the integration of fully dialect-sensitive dictionaries, integrated lemmatization, and AI-assisted annotation features, further strengthening the platform's role at the intersection of traditional expertise and digital innovation.

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## 46. chublets.software – From hidden Little Minions to an Archaeological Research Software Marketplace

*Florian Thiery (LEIZA)*

*Lutz K. Schubert (University of Cologne)*

### Abstract

In archaeological research, research software plays a crucial but often invisible role. Scripts, workflows, and digital tools developed within individual projects, so-called little minions, are rarely findable or documented in ways that allow reuse, interoperability, or long-term sustainability. chublets.software addresses this challenge by creating a FAIR marketplace for Cultural Heritage, related research software, drawing inspiration and data from open-archaeo.info while embedding the initiative within the NFDI4Objects infrastructure and the broader FAIR4RS movement. Especially while looking to research infrastructure initiatives (such as the German NFDI), research serves a huge role in (a) software as a research artefact or (b) software as a FAIRification tool (Thiery et al. 2025b).

The concept builds upon open-archaeo.info, a community-driven registry of archaeology-related scripts and software projects maintained through an open CSV catalogue. This resource already captures a diverse ecosystem of tools, from data-cleaning scripts to 3D visualisation frameworks, but lacks structured metadata, persistent identifiers, and semantic interoperability. chublets.software extends this effort by harvesting, enriching, and curating

the open-archaeo entries inside a Wikibase instance hosted on wiki-base.cloud. Here, each software artefact becomes a structured item described using elements from the Citation File Format (CFF), CodeMeta, and the Hungry Squirrels Ontology, developed by the Research Squirrel Engineers Network.

The Hungry Squirrels Ontology, created some years ago for a little minion catalogue, introduces a playful yet powerful vocabulary for modelling relationships between research software, data, and agents in Cultural Heritage contexts. Combined with DCAT, CFF and CodeMeta, it allows the marketplace not only to expose metadata through Wikibase interfaces and APIs but also to export an RDF representation that can be queried, linked, and reused across the federated Knowledge Graph ecosystem (Thiery et al. 2025a; Fischer et al. 2025). This RDF layer turns chublets.software into more than a catalogue: it becomes a semantic bridge connecting archaeological software projects, research data repositories, and infrastructural registries such as the nfdi.software Basic Service within Base4NFDI.

A distinctive feature of chublets.software is its ability to integrate the so-called Little Minions, small, task-specific research software tools for FAIRification workflows. These “minions” are both practical tools and conceptual metaphors for modular, reusable software building blocks. Each minion, initially described in RDF/Turtle, will be imported into chublets.software as a first-class software entity, complete with metadata, provenance, and links to its source repository. This integration demonstrates how community-developed FAIR software artefacts can be made visible and citable within a shared infrastructural context.

Technically, the workflow consists of several layers:

1. ingestion of existing CSV data from open-archaeo and GitHub repositories;
2. automatic extraction of software metadata from CFF and CodeMeta files using Python scripts;
3. transformation of metadata into Wikibase items aligned with the Hungry Squirrels Ontology;

4. RDF export following DCAT profiles for interoperability with other Knowledge Graph infrastructures;
5. integration with nfdi.software for harvesting and discovery across the NFDI landscape.

This architecture not only supports the FAIR4RS principles but also creates a model for how domain-specific research communities can build lightweight yet semantically rich registries without duplicating central infrastructures. In doing so, chublets.software acts as a disciplinary front end to nfdi.software and a living example of how FAIR software can be collaboratively described, linked, and sustained.

By embedding the Little Minions and the open-archaeo catalogue into a FAIR-compliant Wikibase ecosystem, chublets.software exemplifies the convergence of Research Software Engineering, Semantic Web technologies, and Cultural Heritage research. It transforms scattered, project-specific code into a connected network of reusable software knowledge, inviting archaeologists, developers, and digital humanists alike to contribute, extend, and remix their tools.

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## 47. SPARQLing Unicorn Research Toolkit – Little Minions for FAIR Archaeological Data

*Florian Thiery (LEIZA)*

*Fiona Schenk (Johannes Gutenberg University Mainz)*

*Daria Stefan (TU Wien)*

#### Abstract

In archaeology, many researchers collect, publish, and analyse data across different platforms – from Wikidata and community-driven Wikibase instances to institutional knowledge graphs like the NFDI4Objects Knowledge Graph within the federated Knowledge Graph Ecosystem (Thiery et al. 2025a; Fischer et al. 2025). Yet, querying these Linked Open Data (LOD) resources, combining them across domains, and turning raw RDF into something human-readable often requires technical magic. The SPARQLing Unicorn Research Toolkit is one of those “little minions” that make this magic possible.

Developed as a community-driven FAIRification toolset by the Research Squirrel Engineers, the SPARQLing Unicorn offers lightweight, script-based helpers to transform, query, and visualise RDF data for archaeological and cultural-heritage research. It builds on the idea that every researcher should

be able to access and reuse semantic data without needing to become a SPARQL wizard. The toolkit is open-source, written in Python and JavaScript, and available on GitHub at

- <https://github.com/sparqlunicorn/sparqlunicornGoesGIS> (QGIS Plugin)
- <https://github.com/sparqlunicorn/sparqlunicornGoesGIS-ontdoc> (HTML-generator).

### A Minion with Two Superpowers

The SPARQLing Unicorn has two primary abilities.

(1) It enables FAIR and LOUD querying of distributed RDF datasets via SPARQL endpoints such as Wikidata, FactGrid or the NFDI4Objects Knowledge Graph. With just a few lines of configuration, users can fetch, filter, and visualise Linked Open Data directly in QGIS or Jupyter Notebooks – no need for heavy frameworks.

(2) It automatically generates FAIR-compliant HTML documentation from RDF files. These lightweight static pages are published via GitHub Pages and include all relevant metadata, provenance, and links to original graph resources, turning complex RDF datasets into transparent, reusable research artefacts.

Both functions help bridge the gap between machine-actionable data and human-interpretable research documentation, a central challenge in digital archaeology.

### Use Cases: From Stones to Volcanoes

Several examples illustrate the practical use of these little minions:

- Ogham Stones – Queries combine epigraphic datasets from Wikidata and the NFDI4Objects Knowledge Graph, enabling researchers to map inscriptions in QGIS while simultaneously generating HTML documentation pages for each Ogham Stone, see <https://linkedopenogham.github.io/ogham-lod/>.
- Holy Wells – Data from Wikidata are queried live to create thematic maps of wells associated with specific saints in Ireland, demonstrating how citizen-

science datasets can seamlessly interact with professional research databases, see [https://www.wikidata.org/wiki/Wikidata:WikiProject\\_HolyWells](https://www.wikidata.org/wiki/Wikidata:WikiProject_HolyWells).

- Campanian Ignimbrite – RDF datasets describing volcanic-ash findspots and related analytical data are integrated through federated SPARQL queries, showing the potential of cross-domain semantic modelling between archaeology and geosciences, see <https://research-squirrel-engineers.github.io/campanian-ignimbrite-geo/>.

- Linked Reindeers – A more playful example demonstrating how environmental and faunal data from Wikidata can be visualised in QGIS, encouraging experimentation with semantic-spatial relationships, see [https://www.wikidata.org/wiki/Wikidata:WikiProject\\_LinkedReindeersAlta](https://www.wikidata.org/wiki/Wikidata:WikiProject_LinkedReindeersAlta).

Each example highlights the toolkit's ability to query once, visualise anywhere, and document automatically, the core principles of FAIR and LOUD research.

### Why Use This Minion?

The SPARQLing Unicorn Research Toolkit simplifies tasks that would otherwise require specialised knowledge in RDF syntax, SPARQL endpoints, or Linked Data publishing. It lowers the entry barrier for archaeologists who want to make their data interoperable without losing focus on research questions. By combining semantic querying with automatic documentation, the toolkit contributes directly to FAIRification workflows within open infrastructures like the NFDI ecosystem, ARIADNEplus, or the European Collaborative Cloud for Cultural Heritage (ECCCH). In doing so, it supports the broader movement towards LOUD data – Linked Open Usable Data – that are not only machine-actionable but also accessible, understandable, and reusable by humans. All components are openly available, well-documented, and ready for playful reuse. Whether querying inscriptions, holy sites, volcanic deposits, or animal habitats, the SPARQLing Unicorn Toolkit, as a FAIRification tool (Thiery et al. 2025b), shows how small, open-source scripts can have a significant impact on digital archaeology. Sometimes, all you need is a little minion to make your data sparkle.

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Thiery, Florian, Bernd Flemisch, Beate Hetényi, Corinna Seiwert, Roman Baum, Jan Bernoth, Stephan Ferenz, Jan Linxweiler, Martin Reinhardt, und Lutz Schubert. 2025b. „RSE4Research Data Infrastructures - The Role of Research Software Engineers in creating FAIR Data with FAIR4RS Code“. In Proceedings of the Conference on Research Data Infrastructure 2025, herausgegeben von York Sure-Vetter und Paul Groth, 7(5), Q6, 7(5), Q6. Aachen: Squirrel Papers. <https://doi.org/10.5281/zenodo.16736041>.

## 135. Web scrapping of an archaeological dataset using Python: An ADS bifaces dataset example

*Juan Palomeque-Gonzalez (IDEA- Madrid)*

### Introduction

Access to large digital archaeological datasets often requires repetitive manual interactions with repository interfaces. This creates barriers to reproducibility and restricts the integration of legacy data into new analytical frameworks. The Lower Palaeolithic technology, raw material and population ecology (bifaces) dataset (Marshall et al. 2002), hosted by the Archaeology Data Service (ADS), exemplifies this challenge.

Compiled between 1999 and 2001 under an Arts and Humanities Research Board grant, it contains 10,668 digitised images and metadata for 3,556 bifaces from Africa, Europe, and the Near East. While the dataset has the potential of being a cornerstone for Palaeolithic research, Google Scholar only shows seven citations to said dataset. The ADS interface limits query results and requires visiting individual record pages to access artefact details and standardised photographs, an impractical workflow for large-scale or comparative studies.

Building on recent methodological discussions that promote web scraping as a legitimate research technique in archaeology (Aguilar 2023; Paige 2024; Demir et al. 2023), this project explores how a short Python script can automate data extraction while remaining open, ethical, and compliant with repository terms of use.

### Methods and Materials

A minimal Python script (fewer than 200 lines) was written using the Python libraries requests, BeautifulSoup, and pandas. The script iterates through the known numerical range of record IDs in the ADS biface archive, dynamically generating the URL of each entry. For every page, it performs three main operations:

Artifact data extraction – Parses the HTML structure to obtain artefact ID, provenience, raw material, measurements, and descriptive fields.

Data storage – Appends all parsed data into a pandas DataFrame and exports it as a CSV file for later analysis.

Image retrieval – Identifies and downloads the three standardised photographs associated with each artefact.

To ensure ethical automation, the script development integrated precautions consistent with best-practice guidelines (Paige 2024). The site's



robots.txt file was checked before scraping, a randomised delay between requests was added to avoid overloading the ADS servers, and the ADS Terms of Use and Access were reviewed to confirm that such scraping would be allowed under them. The process was executed on a standard workstation, requiring a few hours to retrieve the full dataset.

## Results

The script successfully automated the collection of all 3,556 records and their associated 10,668 images. The resulting dataset, saved as structured CSV tables and image folders, is now suitable for reproducible computational workflows. Tasks that would otherwise require many hours of manual navigation were completed automatically, demonstrating the efficiency of lightweight automation to gather and structure data, making it available for further analysis.

Preliminary checks confirmed the accuracy of the extracted data and the consistency of image links. The CSV format facilitates direct import into analytical environments (Python, R, or GIS) for further morphometric or spatial analysis. Because the extraction pipeline is transparent and open-source, it can be adapted easily to other ADS collections or similar heritage repositories.

## Discussion

Although technically modest, this script embodies the spirit of the “little minions” described by Thiery et al. (2021): small, self-made helpers that quietly optimise research practice. Following Aguilar (2023), who emphasised web scraping and text mining as methodological bridges between unstructured and structured data in archaeology, the present work shows that even simple automation can extend the usability of existing archives. It transforms a static web interface into a machine-readable dataset, promoting data reuse and reproducibility.

At the same time, the project addresses the ethical and legal considerations outlined by Paige (2024). Transparent identification, compliance with repository rules, and request throttling illustrate how responsible scraping can

coexist with digital heritage stewardship. The approach avoids sensitive or restricted content, adheres to open-data principles, and respects the intellectual ownership of curated archives.

In practical terms, the resulting dataset can be linked to wider infrastructures, supporting FAIR data (Findable, Accessible, Interoperable, Reusable) and open-science practices. The same approach could be reused to harvest structured metadata from other legacy datasets, enhancing cross-project interoperability. This case also highlights an important conceptual point: large-scale digital transformation in archaeology does not always require complex systems or artificial-intelligence pipelines. Sometimes a short, transparent script is enough to make valuable data accessible and to foster community-driven reproducibility.

## Conclusions

This project demonstrates how a short, transparent Python script can transform a manually constrained online dataset into a reproducible, machine-readable resource. By automating the extraction of metadata and images from the Lower Palaeolithic bifaces archive, it enables efficient access to a key dataset that had been technically accessible but practically underused. The resulting CSV and image corpus provide a foundation for quantitative, morphometric, and spatial analyses, as well as integration with other open archaeological datasets. Beyond this specific case, the workflow illustrates how responsible, lightweight automation can extend the usability of legacy digital collections and support reproducible, data-driven archaeological research.

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<https://doi.org/10.31048/1852.4826.v16.n2.41094>

Demir, N., C. S. Boyoğlu, and D. Kayikci. 2023. “A Web Scrapping and AI Approach for Archaeologists to Analyze the Ancient Cities.” *Cultural Heritage and Science* 4 (1): 1–8. <https://doi.org/10.58598/cuhes.1213426>

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Thiery, Florian, et al. 2021. “Little Minions in Archaeology: An Open Space for RSE Software and Small Scripts in Digital Archaeology.” *Squirrel Papers* 3 (4). <https://doi.org/10.5281/zenodo.4575167>

## 223. Wikidata Meets QGIS: Enhancing Archaeological Interpretation with Visual Foundation Models

*Jürgen Landauer (Landauer AI)*

*Florian Thiery (LEIZA)*

Recent advances in visual foundation models (VFM) have enabled a new generation of neural networks capable of seamlessly processing and reasoning over multimodal data such as images and text. Prominent examples include ChatGPT (OpenAI) and Google Gemini, which integrate visual and linguistic understanding within a unified framework. These models have already been successfully applied to remote sensing imagery, including applications in landscape archaeology, where they can analyze satellite or LiDAR data and respond to natural-language queries about the detected features or structures (Landauer and Klassen 2025).

Building on this potential, we have presented LandTalk.AI (Landauer 2025), a QGIS plugin developed to demonstrate the use of VFMs for interactive archaeological interpretation. Users can provide geospatial imagery and directly query the system – for example, to classify or describe archaeological features – through a conversational interface.

In this research, we further investigate the efficacy of Retrieval-Augmented Generation (RAG) for enhancing the interpretive capabilities of VFMs in archaeological contexts. RAG architectures combine generative models with external data sources, such as structured databases or web repositories, to improve factual grounding and domain specificity. While RAG has shown substantial promise in other scientific and technical fields, its potential for archaeological remote sensing and data integration remains underexplored.

We demonstrate how combining VFMs with RAG enables richer, context-aware analyses by linking visual interpretation to curated archaeological datasets and open knowledge sources (e.g., Wikimedia Commons, heritage databases). Our findings highlight the transformative potential of this approach for digital archaeology, particularly in fostering accessible, explainable, and data-driven landscape interpretation workflows.

To further enhance contextual understanding, we extend the RAG pipeline with semantic grounding using Wikidata Q-IDs (Schmidt, Thiery, and Trognitz 2022). Users can specify entity identifiers – such as hillfort (Q744099), castle ruin (Q109607), or medieval period (Q12554) – to clarify the intended meaning of their queries. These identifiers are passed to the language model as structured context, linking visual interpretation to precise, machine-actionable concepts. This direct semantic handover improves factual consistency and domain awareness, enabling the AI to reason within archaeological ontologies rather than relying solely on linguistic associations.

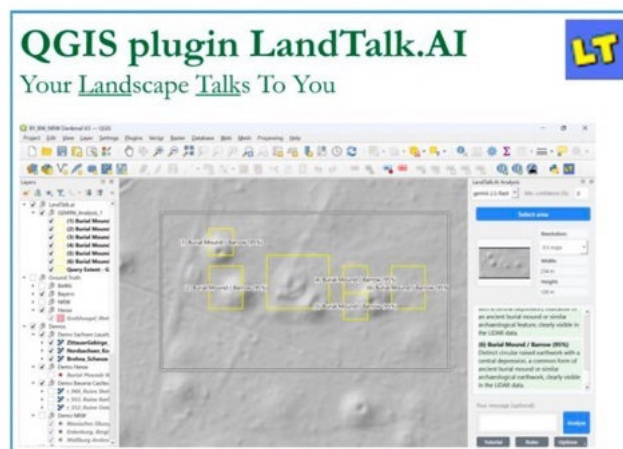


Fig. 1: QGIS Plugin LandTalk.AI

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## 238. Secanto - Recent developments

Vincent Mom (DPP)

## Introduction

Secanto (the Section Analysis Tool) was originally developed as a tool to compare the shapes of simple archaeological artifacts (ceramic vessels, arrow points, stone axes), producing objective quantifiers that are independent of the researcher who did the comparison: "The shape of vessel A looks more like the shape of vessel B than the shape of vessel C", with a numeric substantiation to underpin such statement (Author 2007).

In 2019, a generalization of the method followed: based on a *multi-site* collection of items, the researcher could then make the following types of site-level statements: "Based on comparisons of shapes of vessels, site A looks more like site B than like site C" (Author 2019).

With this presentation we want to introduce the latest enhancement of Secanto that addresses one old criticism that was around since day one the method was introduced: Secanto only works properly with complete items, but not with incomplete items.

## Data set used

In 2008, Beckerman and Raemakers published an article with a new typochronology of ceramics of the Vlaardingen group, found in the southwestern part of The Netherlands (3400-2500 BC) (Beckerman and Raemakers 2008). Their data set consisted of 7 complete vessels, and 39 (large) rim-fragments. By visually matching the vessels and the rim-fragments the authors determined 5 different shape groups (A, B, C, D, E, colored accordingly in Fig. 2). All items, vessels and rim-fragments, were scaled to a rim diameter of 5 centimeters.

The Secanto experiment with this small data set should be considered as a 'proof of concept'. Secanto projects usually involve hundreds of objects (e. g. the Santana de Mureș-Černjachov sites of Bârlad (634 vessels) and Mihălășeni (1067 vessels) respectively (Author 2019))

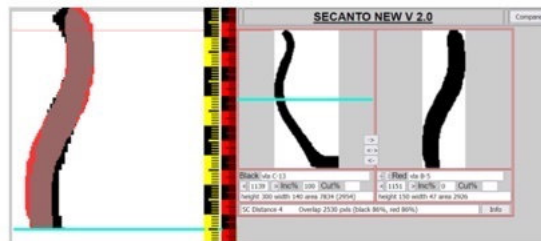


Fig. 1a: A comparison of a complete vessel (C-13) with a rim fragment (B-5)

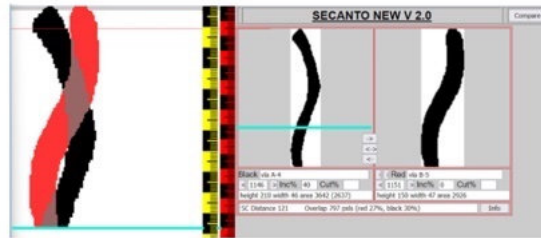


Fig. 1b: A comparison of two rim fragments, A-4 and B-5

## Method

The Secanto approach differs in several ways: first, rim diameters were *not* used for scaling. Instead, all the images, both vessels and fragments, are scaled to a vertical height of 150 pixels. If the comparison is between a complete vessel (CV) and a rim fragment (RF) then the average wall width of the CV was recalculated and set equal to the average wall width of the RF. This rescaling of the CV increases the height of the CV, and therefore the lower part of the vessel was removed to obtain, again, an image height of 150 pixels. Or, in other words: the CV was turned into an RF with the same wall width of the RF to do the comparison with. Next, a standard Secanto calculation was performed, resulting in a value for the shape difference between the two items. Figure 1a shows a CV / RF comparison. The part of the CV below the blue line is removed.

If the comparison is between two RFs, the average wall widths of the two items is set to the same value, and the two images are rescaled to a height of 150 pixels. Figure 1b shows an RF / RF comparison.

## Data visualization: PCA versus t-SNE

Once a  $N*(N-1)$  pairwise shape difference matrix is calculated for the set of  $N$  objects, a range of standard statistical techniques is available for further analysis. For Secanto sets with complete vessels, 2D visualization using Principal Coordinate Analysis usually provides satisfactory results, as the two major eigenvalues make up more than 95 % of the whole  $N$ -dimensional space. These two PCA eigenvalues correspond with (1) the ratio of height and maximum belly diameter of the vessels, and (2) the degree of 'openness' of the vessels (See Author 2019, figure 3 and table 1).

However, for a heterogeneous, 'mixed' data set with both complete vessels and rim fragments, the sum of the 2 largest PCA eigenvectors does not rise above 60%, and assigning a physical interpretation to the eigenvectors is not possible. In this case, the alternative t-Distributed Stochastic Neighbor Embedding method (t-SNE) is more appropriate.

t-SNE is a technique for dimensionality reduction that is particularly well suited for the visualization of high-dimensional data sets. The technique is available through open source software, and Matlab and SPSS contain standard t-SNE functionality. Van der Maaten applied it on data sets with up to 30 million records (Van der Maaten and Hinton 2008).

t-SNE has several run time parameters, and for small data sets Perplexity and Exaggeration are the most important ones. Especially Perplexity, a measure for the number of closest neighboring records, provides ample possibilities for experimenting with different visualizations (Figure 2).

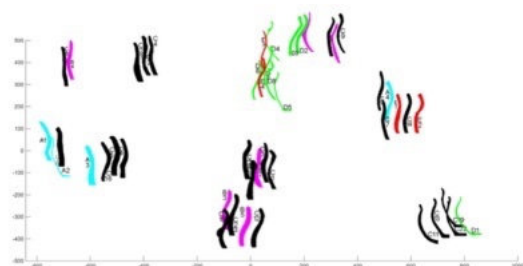


Fig. 2c: Visualization of the CV/IRF data set using t-SNE. Perplexity = 2

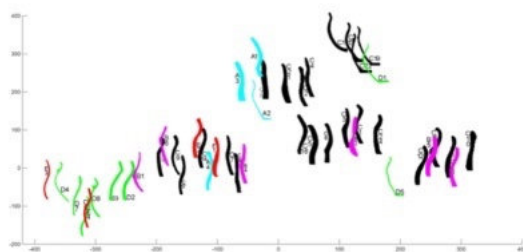


Fig. 2b: Visualization of the CV/IRF data set using t-SNE. Perplexity = 5

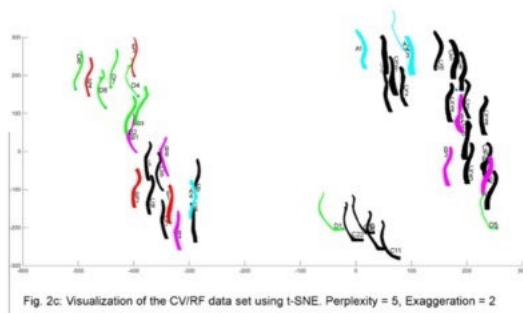


Fig. 2c: Visualization of the CV/IRF data set using t-SNE. Perplexity = 5, Exaggeration = 2

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Author 2007 Where did I see you before ... A holistic method to compare and find archaeological

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### 273. TagLab - a semantic segmentation tool. Now, also for CH

Marco Callieri (ISTI-CNR)

Gaia Pavoni (ISTI-CNR)

Massimiliano Corsini (ISTI-CNR)

Federico Ponchio (ISTI-CNR)

Alessandro Muntoni (ISTI-CNR)

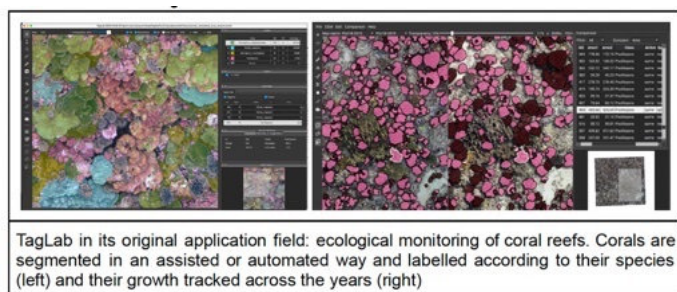
Paolo Cignoni (ISTI-CNR)

Semantic segmentation is a widespread image analysis task: it basically consists in defining areas of the image and labeling them according to their nature and characteristics. TagLab [1] is an open source, AI-powered semantic segmentation software designed to support the analysis of large orthographic images. TagLab provides an assisted annotation workflow, integrating AI and computer vision algorithms for the interactive pixel-wise region



segmentation, and a fully automatic learning pipeline that assists the users in developing automatic semantic segmentation models.

TagLab follows the human-in-the-loop paradigm. This human-machine interaction improves the accuracy of fully automatic predictions and makes full use of the user's expertise. TagLab speeds up the manual annotation through a combination of AI-assisted tracing algorithms and specialized tools, thus helping the manual work of the experts on smaller datasets or to create training datasets. For a more automated approach, the user can use the Train-Your-Network feature to obtain a custom CNN for the semantic segmentation, based on the training data produced in the previous step. This trained model can then be used to automatically annotate new unlabelled orthoimages. After this automatic classification, the human expert can re-enter the annotation loop and correct the errors with the editing tools, thus improving the results and the performance of the CNN. TagLab offers a variety of raster and vector outputs to use the annotated data in other tools, and a set of functionalities to compute geometric, metric, and statistical information over the annotated images, to support deep analyses of the result of the segmentation.



TagLab has been initially designed and developed for marine biology research, in particular, for monitoring coral reefs. However, as most of its functionalities are agnostic (i.e., will work on any subject), its application to other fields was a natural step.

The first experiments were carried out on historical masonry [2], where TagLab was used to segment areas of uniform techniques/materials of built heritage: a task often carried out in the conservation of large structures to evaluate their structural soundness. The experimentation was successful, resulting in an increased speed and accuracy in the assisted annotation process with respect to the standard vector/raster tools. The orthoimages annotated by experts were then used to train a CNN that was able to automatically segment unseen data with reasonably good results.

The work in this application field is still ongoing, and thanks to the inclusion of new segmentation tools has moved from large areas to the individual constitutive elements (bricks, stones). The work is focusing on both engineering (structural assessment) and archeological (mural stratigraphy) research questions. New functionalities have also been added for extracting metric, geometric, structural and statistical information to analyze in depth the constitutive elements of built heritage.

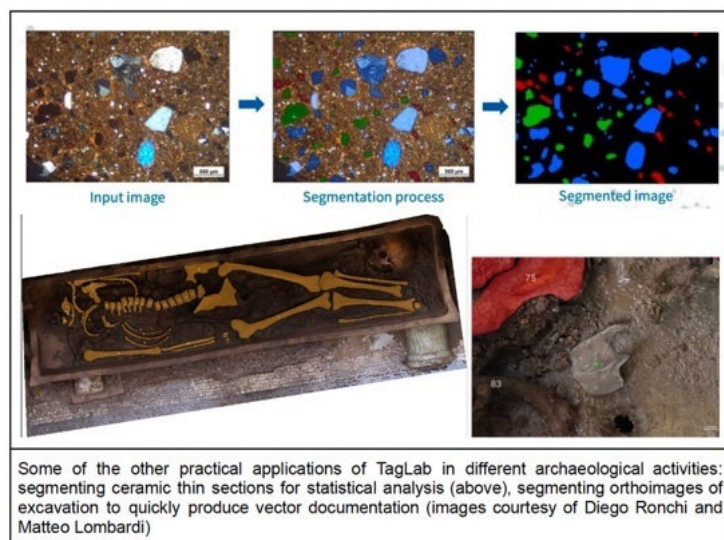


More recently, we started presenting TagLab to the CH community with spot training initiatives. The tool was effectively used by archaeologist in different activities [3], such as tracing findings in excavations, annotating ceramic thin



sections for statistical analysis of fabric types, segmenting built heritage elements for building energetics evaluation, annotating fragments and supports parts of wall paintings for documentation and conservation.

This experimentation demonstrated the versatility of the tool, and how it was possible to include it in the standard working pipeline. Although all these results were all related to the assisted annotation (performed by human experts using the AI and Computer Vision functionalities of TagLab), experiments with the training of specialized CNN for the automated segmentation are ongoing.



The intent of this submission is to present TagLab to the archaeological community at CAA as a tool that can be easily integrated in different workflows, supporting the work of experts. TagLab is an open source software, developed and maintained by a research institution, making it an ideal tool for scientific work, as it fulfills the openness and reproducibility requirements of FAIR workflows. The development is ongoing, and new functionalities are being added to the tool, improving all the phases of the workflow: assisted and

automated segmentation (adding new models, such as YOLO) and export / analysis of annotated areas.

WEBSITE: <https://taglab.isti.cnr.it/>

GITHUB REPO: <https://github.com/cnr-isti-vclab/TagLab>

[1] TagLab: AI-assisted annotation for the fast and accurate semantic segmentation of coral reef orthoimages

G. Pavoni, M. Corsini, F. Ponchio, A. Muntoni, C. Edwards, N. Pedersen, S. Sandin, P. Cignoni

Journal of field robotics 39 (3), 246-262

DOI: 10.1002/rob.22049

[2] On assisting and automatizing the semantic segmentation of masonry walls. G Pavoni, F. Giuliani, A. De Falco, M. Corsini, F. Ponchio, M. Callieri, P. Cignoni

ACM Journal on Computing and Cultural Heritage (JOCCH) 15 (2), 1-17. 2022

ISSN: 1556-4673, DOI: 10.1145/3477400

[3] Outside the Wall: Some Applications of TagLab for Semantic Segmentation in Archaeological Practice.

D. Ronchi, E. Di Virgilio, S. Mele, M. Lombardi, D. Ferdani, D. Dinunno

Proceedings of Digital Heritage International Congress 2025.

ISBN: 978-3-03868-277-6, DOI:10.2312/dh.20253035

## 281. QSKOS. Development of a plugin for integrating controlled vocabularies into QGIS

*Lasse Mempel-Länger (LEIZA)*

*Anja Cramer (LEIZA)*

*Benjamin Streubel (LEIZA)*

*Kristina Fischer (LEIZA)*

*Florian Thiery (LEIZA)*

*Ingrid Stelzner (LEIZA)*

*Nico Wende (LEIZA)*

*Allard Mees (LEIZA)*

### Introduction

Geographic information systems (GIS) such as the free open-source software QGIS have become established for the digital documentation of spatial archaeological findings. They are equally suitable for documenting conservation features such as damage patterns and interventions on archaeological objects.

This documentation of the archaeological source is necessary in order to record information about its manufacture or signs of use, but also to record changes in its condition, whether due to deterioration or conservation measures.

To ensure data quality and sustainable data provision in accordance with the FAIR principles (Findable, Accessible, Interoperable, Reusable), the use of controlled vocabularies is recommended. Standardisation of terminology promotes both internal data consistency and efficient, interdisciplinary data exchange between projects and institutions.

However, there is currently no standardised procedure for attributing conservation features in QGIS. In this context, we have initiated a project to integrate subject thesauri for documenting features in QGIS (Last name 2025).

### Methods and materials

Roman leather shoes as archaeological objects are the basis for our use case. The measured orthometric 2D views (GeoTIFF) of the top and bottom of these finds form the mapping basis for the annotation of preservation features in QGIS (Last name u. a. 2025).

Until now, the documentation concept for annotation has been defined individually for each object and user, providing information on geometry type, columns and attributes. This has then been implemented in QGIS and the attribute forms were configured and designed accordingly. These processes are extremely time-consuming and prone to errors.

In order to automate this work for future documentation projects, an interdisciplinary team from the fields of archaeology, conservation, surveying and research software engineering collaboratively designed, developed and tested a QGIS plugin. It enables the direct integration of controlled vocabularies and provides a visual representation of their hierarchical structure in tree views, enabling easy definition of columns and attributes of vector data. In addition, the plugin configures the attribute forms mask for annotation and defines styles for the graphical representation of features. It supports common thesaurus file formats such as Turtle and JSON-LD and stores all QGIS-data in the open file format GeoPackage. Within the use case, the technical feasibility and subject-specific requirements are continuously coordinated to ensure a user-oriented solution that also complies with FAIR principles .

### Results

The developed in-house application is capable of automating workflows that were previously performed manually, thereby substantially reducing the necessary workload.

The plugin first creates a table in the SKOS schema with the properties concept (URI), prefLabel, definition, broader and inScheme from a remotely or locally accessible controlled vocabulary (ttl, jsonld), saves the table in the GeoPackage-file and loads it directly into the QGIS project.

Feature layers in QGIS projects can be linked to such a vocabulary table. The plugin displays the prefLabel of the vocabularies table in a tree view and allows concepts to be selected via checkboxes. Selecting the concepts automatically creates new attributes in the feature layer. Permissible entries for the attributes are their hierarchically subordinate concepts, whose URIs are automatically defined as possible value ranges in the attribute input mask. In addition, the plugin provides a functionality that enables the creation of a rule-based symbology that takes into account all concepts used for annotation as well as their ancestors. For example, if the property Material is annotated as leather for one of the features, it is also displayed as animal skin and collagenous material and finally animal material. Assuming there is suitable vocabulary for the subject area to be annotated, the plugin offers researchers in every discipline the opportunity to systematically tag their spatial research data with controlled vocabularies.

#### Discussion

As a FAIRification tool, the QGIS plugin enables the comparability of digital data internally and across projects and institutions.

This methodically strengthens archaeological as well as conservation documentation and promotes the provision of conservation data for interdisciplinary scientific discourse.

The compilation of a comprehensive dataset comprising the object's description, construction details, condition, and conservation measures also enables a holistic analysis of the object.

In order to further promote connectivity to the Linked Open Data world (Last name u. a. 2022), a suitable RDF model has already been developed. Based on CIDOC CRM, the GeoSPARQL Ontology, the Simple Features Vocabulary, SKOS and the Web Annotation Vocabulary, this model can be used to describe objects, their spatial features and their annotations as triples using SKOS concepts. A function for exporting this data is currently under development.

#### References:

Last Names, First Names. 2025. „Mapping Roman leather shoes using a controlled vocabulary“. Conference paper presented on Wet Organic Archaeological Materials Conference 15-19 September 2025, Göteborg. Proceedings of the 16th Conference of the ICOM-CC Wet Organic Archaeological Materials Working Group, ICOM-CC: Paris. <https://www.icom-cc-publications-online.org/7003/Mapping-Roman-leather-shoes-using-a-controlled-vocabulary>.

Last Name, First Name. 2025. leiza-rse/QSKOS: First alpha release. Zenodo, released November 5. <https://doi.org/10.5281/zenodo.17531697>.

Last Names, First Names. 2022. „Practices of Linked Open Data in Archaeology and Their Realisation in Wikidata“. Digital 2 (3): 333–64. <https://doi.org/10.3390/digital2030019>.

## 282. The "QSaurus". A QGIS-Plugin to implement (SKOS) Thesauri into QGIS

*Brigit Danthine (Austrian Archaeological Institute)*

*Sinan Zülfikar (Austrian Archaeological Institute)*

#### Introduction

The QGIS plugin 'QSaurus' [1] streamlines the integration of controlled vocabularies (thesauri) into geospatial data workflows. Originally developed for the Austrian Archaeological Institute (OeAI), the "QSaurus" addresses a common need in cultural heritage and archaeological projects: consistent, standards-based terminology directly at the point of data entry. The plugin enables users to connect curated vocabularies, select terms, and bind them to layer attributes with minimal configuration. While optimized for OeAI thesauri - exposed via dedicated checkboxes - QSaurus is deliberately generic and can incorporate any SKOS-based vocabulary that satisfies defined structural requirements.

## Methods and materials

The “QSaurus” operates at the layer–attribute level within QGIS. Users select a target vector layer and an attribute field; upon the button “Load terms into attribute table”, the plugin automatically switches the field’s editor widget to Value Map and populates it with selected vocabulary entries, assigning each entry as both Value and Description. This operation is non-destructive: existing terms are neither modified nor removed.

Term selection supports standard interaction patterns: Ctrl for discrete multi-selection, Shift for contiguous ranges, and a rubber-band (“window”) selection across expanded nodes. A built-in search highlights matching strings and auto-expands relevant branches to aid discovery.

Preconfigured sources include the two vocabs-thesauri “OeAI Cultural Periods” [2] and “OeAI Materials” [3]. Additional vocabularies can be registered in two ways: (i) by linking or loading a Turtle (.ttl) file that provides SKOS:prefLabel for labels and SKOS:broader for hierarchy, or (ii) by importing a CSV whose hierarchical levels are mapped to columns named. An optional setting loads English labels (instead of german) for the OeAI vocabularies where available.

Because QGIS persists editor widgets and value maps in layer styles, the “QSaurus” saves the updated style automatically to the project’s GeoPackage or as a .qml file named “qsaurus\_n” (ordinally incremented), enabling effortless reuse across projects.

## Results

The “QSaurus” embeds controlled vocabularies directly into attribute editing, producing immediate gains in data consistency and entry speed. In practice, users can: (1) bind one or more curated thesauri to selected attribute fields without manual widget configuration; (2) quickly filter and navigate large hierarchies via search-driven expansion; (3) bulk-apply sets of terms using common selection metaphors; and (4) persist configured value maps as reusable styles. The non-destructive population logic preserves legacy value maps, ensuring backward compatibility with existing datasets. Support for SKOS/Turtle and structured CSVs allows rapid onboarding of institution-

specific vocabularies beyond the OeAI defaults. Where bilingual labels exist, optional English term loading enhances interoperability in international projects.

## Discussion

By coupling vocabulary management with QGIS’s native Value Map widget and style system, the “QSaurus” minimizes friction between standards-compliant terminology and everyday digitizing tasks. This approach avoids bespoke dialogs or external editors, favoring reproducible configurations stored alongside layers. The reliance on SKOS (prefLabel, broader) ensures compatibility with widely adopted publishing practices, while the CSV pathway offers a pragmatic route for teams without RDF infrastructure. Limitations include the current absence of recursive selection and a default maximum of seven hierarchy levels in CSV imports; both are transparent, configurable constraints with clear workarounds (expand-all + window selection; parameter adjustment).

Overall, the “QSaurus” lowers the barrier to operationalizing controlled vocabularies in geospatial heritage workflows, supporting consistent semantics, higher data quality, and reusable, style-based configurations across QGIS projects.

[1] <https://github.com/oeai-dac/QSaurus>

[2] <https://vocabs.acdh.oeaw.ac.at/oeai-cp/en/>

[3] [https://vocabs.acdh.oeaw.ac.at/oeai-materials\\_browse/en/](https://vocabs.acdh.oeaw.ac.at/oeai-materials_browse/en/)

### 395. MergeLines: a tool to merge adjoining linear structures based on contiguity angles

*Nathanaël Le Voguer (UMR 7324 CITERES-LAT)*

Disclaimer: A prior version of this abstract was submitted for the Little Minions session of the CAA in 2020. The conference was cancelled and this abstract was never published or proposed elsewhere since.

Link to the script: [https://gitlab.huma-num.fr/nlevoguer/scripts-de-these-le-voguer/-/blob/27fddf60dbd8b1a782a30e6c3f5b10850314ae34/MergeLines\\_2.5.1.py](https://gitlab.huma-num.fr/nlevoguer/scripts-de-these-le-voguer/-/blob/27fddf60dbd8b1a782a30e6c3f5b10850314ae34/MergeLines_2.5.1.py)

#### Abstract

The spread of LiDAR data in the archaeological world opened up new challenges for small scale study of parcel networks. In the Centre-Val de Loire region of France, tens of thousands of interconnected embankments were discovered, forming line networks spreading on hundreds of square kilometres. These embankments were primarily studied through their morphology, creating classes based on several parameters, including width, height, volume and length.

The length of the structures could not be based on how they were drawn, but had to be calculated on how they were, structurally. The goal of the tool ("MergeLines") is to create a more accurate representation of these linear structures. It uses ArcGIS and ArcPy tools and features. It is useful for the analysis of networks of linear structures such as roads or parcel boundaries (embankments, ditches...).

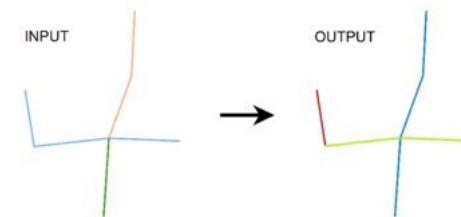
The idea behind the script was to break down the structures to the most fundamental element (one line, two vertices) and then merge the ones connected to each other based on the angle between the two lines (see figure). As input, the user provides a threshold angle at which the merging may

occur. This angle may be different based on the context in which we use the tool.

The tool uses the cursor object in ArcPy which iterates over a set of rows in a table. The cursor will read a first line, select the other lines touching it and calculate the angle between them and the original one. These angles are written in a new column and stored in a list. Once all the angles for connected lines are calculated, the line with the smallest angle (if it is inferior to the threshold angle) is merged to the first one. Once every feature has been passed through like this, the cursor resets and goes through each of them again, until there is no possibility for merging any more.

This small script was necessary to use the length of structures as a morphological characteristic. It has been used successfully in a research project with hundreds of thousands of embankments, proving useful to identify outstanding axes in the network and do more advanced statistical analyses. The script can be used in Arcmap as part of a toolbox and does not necessitates for the user to know any python programming.

Furthermore, I am currently working on adapting the tool for QGIS, which is the software I use almost exclusively today. The goal is to provide this tool as an independent plugin, for QGIS, by the beginning of next year.



## 416. STON: a practical imaging tool for archaeological petrography and beyond

*Evgenia Dammer (Rathgen Research Laboratory)*

*Romain Thomas (University of Sheffield)*

STON (SoFTware for petrOgraphic visualisation) is open-source software designed to make microscopic image analysis faster and easier for archaeologists. Petrographic analysis in archaeology involves the systematic comparison of numerous thin-section samples to address fundamental questions of technology and provenance—determining how ceramic objects were manufactured and where their raw materials originated (Quinn 2022). Unlike existing microscopic imaging software, which is primarily built for geological research and the natural sciences, STON is tailored to archaeological research needs, allowing users to cluster and compare multiple images simultaneously in a simple, user-friendly workspace. This visualisation tool enhances the efficiency of petrographic grouping and ceramic paste analysis by enabling users to view, manually sort, and cluster large sets of image data in one workspace.

Key features include freehand sorting, side-by-side scrolling, and synchronised zoom of photomicrographs or thin-section scans. By streamlining these processes, STON enhances not only ceramic paste analysis and petrographic grouping but can be applied to any project involving the systematic comparison of large image datasets. The application of microscopy in archaeological research extends beyond petrography to include both organic and inorganic materials, all sharing the same fundamental analysis methods: comparison, grouping, and detailed study of characteristics across multiple samples.

Developed openly on GitHub, STON is designed as a sustainable tool, free to use and fully adaptable. The Python-based source code can be customized to meet the specific needs of individual projects involving image data analysis. The tool is developed using Python-pillow (Murray et al. 2025) and matplotlib for image display and operation, and scikit-image (van der Walt et al. 2014) for deeper image processing.

Link to repository <https://github.com/Romain-Thomas-Shef/STON>

Link to publication <https://doi.org/10.21105/joss.08144>

### References:

Murray, A., H. van Kemenade, wiredfool, J. A. Clark, A. Karpinsky, O. Baranovič, C. Gohlke, Yay295, J. Dufresne, M. Brett, DWesl, D. Schmidt, K. Kopachev, A. Houghton, REDxEYE, S. Mani, S. Landey, A. Koskela, R. Keith-Magee, and S. Kossouho. 2025. "Python-pillow/pillow: 11.1.0." Version 11.1.0. Zenodo. <https://doi.org/10.5281/zenodo.14586647>.

Quinn, P. S. 2022. Thin Section Petrography, Geochemistry and Scanning Electron Microscopy of Archaeological Ceramics. Oxford: Archaeopress Publishing Limited.

van der Walt, S., J. L. Schönberger, J. Nunez-Iglesias, F. Boulogne, J. D. Warner, N. Yager, E. Gouillart, T. Yu, and the scikit-image contributors. 2014. "Scikit-image: Image Processing in Python." PeerJ 2: e453. <https://doi.org/10.7717/peerj.453>.

## 444. Digging for Answers: Unearth the Most Suitable Machine Learning Model

*Daria Stefan (TU Wien)*

*Iris Grze (TU Wien)*

The integration of machine learning (ML) into archaeological research has accelerated in recent years, supporting diverse tasks such as artifact classification, site prediction, and textual analysis. Yet, the proliferation of heterogeneous methodologies and the lack of standardized evaluation protocols impede reproducibility and comparative assessment across studies.



This paper presents a Python-based Minion, implemented within the Jupyter ecosystem, that enables systematic comparison of ML approaches on archaeological data. The tool provides a reproducible experiment management framework encompassing dataset versioning, model tracking, and detailed documentation of training, validation, and testing configurations. It supports the computation and visualization of a wide range of performance metrics, such as precision, recall, F1-score, area under the curve (AUC), facilitating transparent cross-model evaluation.

As a representative case study, the tool is applied to a dataset containing Slovenian inscriptions provided by the Europeana Eagle project, with translations available in MediaWiki. This dataset serves as a benchmark corpus for testing multiple ML approaches on archaeological data, such as multi-class classification (e.g., inscription type, material, or provenance), regression (chronological estimation), clustering (regional or typological grouping), and information extraction from epigraphic text. By integrating open-source Python libraries, reproducible Jupyter workflows, and FAIR4ML-compliant metadata management, this Minion provides a reusable and transparent framework that assists researchers in selecting the most appropriate ML approach based on the characteristics of their data and research objectives.

Caravale A., & Duran-Silva N., & Grima B., & Moscati P., & Rondelli B. (2023). Developing a digital archaeology classification system using Natural Language Processing and Machine Learning techniques, *Archeologia e Calcolatori*, 34(2), 9-32.  
<https://doi.org/10.19282/ac.34.2.2023.01>

Bickler, S. H. (2021). Machine learning arrives in archaeology. *Advances in Archaeological Practice*, 9(2), 186-191.

Bickler, S. H. (2021). Machine learning arrives in archaeology. *Advances in Archaeological Practice*, 9(2), 186-191.

## 446. Data driven landscape reconstruction for Blender Software

*Marti Košťál (Masaryk University)*

Although the generation of virtual reconstructions of small scale scenes (artefacts, houses) has advanced to an entirely new level in recent years (Ferdani et al., 2020), the reconstruction of entire landscapes remains significantly limited (Ciccone et al., 2025). This is due to the scale of 3D landscape scenes, which impose high hardware demands, but above all to the complexity and diversity of anthropogenic landscapes, which are very difficult to capture through subjective and manual work. The hardware aspect is closely tied to the need for optimization of what happens “under the hood” (e.g., optimization of 3D models through LOD systems) within the chosen visualization tool (Blender, Unreal Engine, Houdini, etc.).

This presentation introduces a tool that enables automated and parameterized landscape reconstruction, allowing the use of vector land-use maps (e.g., imported from GIS) as input data. The tool provides fast and intuitive editing, made possible by its direct implementation in Blender using Python and the integrated visual programming system Geometry Nodes. The Blender software was chosen based on the free accessibility and its long-term usage in the archaeological practice (Demetrescu - Fanini, 2017).

### References:

Ciccone, G., Frisetti, A., Abate, N., Goffredo, R., Dato, G., Amodio A.M., Sileo, M., Lasaponara, R., Masini N., 2025: Unveiling medieval landscapes: A virtual reconstruction through LiDAR and extended matrix methodology, the case of Torre di Castiglione (BA), *Digital Applications in Archaeology and Cultural Heritage*, Volume 39, 2025, e00464, ISSN 2212-0548, <https://doi.org/10.1016/j.daach.2025.e00464>. (<https://www.sciencedirect.com/science/article/pii/S2212054825000669>).

Demetrescu, E., Fanini, B., 2017. A white-box framework to oversee archaeological virtual reconstructions in space and time: Methods and tools. *Journal of Archaeological Science: Reports* 14, 500–514.

<https://doi.org/10.1016/j.jasrep.2017.06.034>.

Ferdani, D., Demetrescu, E., Cavalieri, M., Pace, G., Lenzi, S., 2020. 3D Modelling and Visualization in Field Archaeology. From Survey To Interpretation Of The Past Using Digital Technologies. *GROMA*, 4 1–21.

<https://doi.org/10.12977/groma26>.

## S3: Methodological and Theoretical Research in Digital Archaeology

*Anja Wutte, University of Cologne, Germany; TU Wien, Austria*

*Maria Sotomayor Chicote, University of Cologne, Germany*

**Location:** Auditorium Maximum

**Session Format:** Standard

Methodological and theoretical research in computational archaeology, perhaps with a few exceptions, is mainly characterised by the adoption of methods and theoretical concepts from other disciplines. What can be regarded as theoretical archaeology is primarily the import of methods that are adopted and applied by archaeologists, but little discussed and not significantly further developed. These methods, of course, have a theoretical basis, which is then also referred to in the publications or summarised. However, it usually remains an application to archaeological sources, which is neither about a critical ‘review’ of the underlying theory nor about its further development, but primarily about gaining more, better or even just different insights into the past. To put it somewhat cynically, the impression rises that there is still no theoretical archaeological discourse. (Atzbach 1998; Karl 2015; Rebay-Salisbury 2011).

This session therefore emphasises the need for and importance of methodological and basic research in digital archaeology. The topics of submitted papers may cover, but are not limited to, the following topic groups.

**Archaeotecture:** Projects and work in the interconnecting field of archaeology and architecture focus on the development of innovative digital methods in relation to architectural cultural heritage and include areas of building recording, data processing, documentation and the development of customised analysis options.

**Technical innovations and Solutions:** Technical innovations and solutions play an important role in the further development of archaeological

research. Archaeologists use technical means to support and expand traditional methods. They have a major impact in the processes of searching, analysing, documenting and presenting finds. Existing solutions are usually adapted for this purpose, but archaeologists themselves can also contribute to improving technical processes and establishing innovative solutions. This sub-area aims to create space to advance modern archaeology on a technical level.

**AI in Archaeology:** Artificial intelligence has fundamentally changed the possibilities and forms of archaeological research of visual data. Large amounts of data can be analysed and processed in a short time, which optimises long-term research by saving human and financial resources. AI can support archaeologists in their work and establish itself as a strategic tool. For this reason, one section is dedicated to projects that deal with the further development and adaptation of AI-supported methods for archaeology.

**Spatial Relation and Modelling:** Major goals of archaeology are to document archaeological cultural variability, understand culture-environment relationships, human-landscape interaction and in general describe and understand the behaviors of past populations (Banks, 2017). Considering this, interaction of various kind is the main driver of historical, cultural, social and economic processes. Archaeologists very frequently deal with variants of interaction while there is still room for improving a generalised concept of interaction (Nakoinz 2013).

**Digital Data Management:** Archaeologists increasingly rely on digital data. A successful data management concept concerns data storage, archiving and preservation as well as data accessibility and usability. Therefore, this topic is dedicated to best practice achievements and organisation of digital archaeological materials.

**Teaching and Education:** Digital archaeology is transforming not only research, but also how we teach and engage with archaeological knowledge. This section explores how methods such as archaeogaming, gamification and digital simulations support critical pedagogy in classrooms and museums. We welcome works that reflect on digital tools as spaces for theoretical exploration, methodological training and public engagement.

We invite contributions from all backgrounds and research areas that reflect on the role of archaeology within the wider scientific and technological landscape. This session aims to foster critical discussion around the adoption, implementation and development of digital methods. We particularly welcome interdisciplinary approaches and methodological innovations applicable across different archaeological contexts. Theoretical papers reflecting on these aspects are equally encouraged.

## References:

Atzbach, Rainer. 1998. „Vom Nutzen und Nachteil der Archäologie. Ein Aufruf zur Theoriediskussion.“ *Archäologisches Nachrichtenblatt*, 3–5.

Banks, William E. 2017. „The application of ecological niche modeling methods to archaeological data in order to examine culture-environment relationships and cultural trajectories“, *Quaternaire*, 28 (2), 271–76.  
<https://doi.org/10.4000/quaternaire.7966>.

Karl, Raimund. 2015. „Wo ist die Grundlagenforschung“, *Ethnographisch-Archäologische Zeitschrift*, 56.1/2, 50-53.

Nakoinz, Oliver. 2013. „Spatial Models of Interaction and Economic Archaeology“, *Metalla*, Nr. 20.2, 87–115.

Rebay-Salisbury, Katharina C. 2011. „Thoughts in Circles: Kulturkreislehre as a Hidden Paradigm in Past and Present Archaeological Interpretations“, In: Benjamin W. Roberts and Marc Vander Linden (eds.), *Investigating Archaeological Cultures*, 41–59. New York, NY: Springer New York.  
[https://doi.org/10.1007/978-1-4419-6970-5\\_3](https://doi.org/10.1007/978-1-4419-6970-5_3).

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| <b>10:30 –<br/>10:50</b> | 354. Beyond Borrowed Tools: Towards a Theoretical and Methodological Framework for Digital Archaeology<br><i>Anja Wutte (University of Cologne, TU Wien); Maria Sotomayor Chicote (University of Cologne)</i> |
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| <b>10:50 – 11:10</b> | <p>336. Modular Research Pipeline: Conceptual Work Towards Describing Intentful Research Workflows<br/> <i>Andrea Göhring (Leibniz Laboratory for Radiometric Dating and Isotope Research, *)</i>; <i>Steffen Strohm*</i>; <i>Daniyal Kazempour*</i>; <i>Hendrik Raese*</i></p> <p><i>* Kiel University</i></p>       |
| <b>11:10 – 11:30</b> | <p>10. Handling the Past: Methodological Reflections on Object Interaction in Physical and XR Archaeological Contexts<br/> <i>Despoina Sampatakou*</i>; <i>Andreea Caragea*</i>; <i>Ross Johnstone*</i>; <i>Iain McLean*</i>; <i>Kieran Waugh*</i>; <i>Julie Williamson*</i></p> <p><i>*University of Glasgow</i></p> |
| <b>11:30 – 11:50</b> | <p>134. Design and Evaluation of a Low-Cost IoT Wireless Sensor Network for Environmental and Behavioural Monitoring in Cultural Heritage Structures and Collections<br/> <i>Juan Palomeque-Gonzalez (IDEA- Madrid)</i></p>                                                                                           |
| <b>11:50 – 12:10</b> | <p>25. Potential dwelling structures of the Upper Palaeolithic in Western, Central, and Eastern Europe: A computer-aided quantitative analysis<br/> <i>Dennis Batz (University of Cologne)</i>; <i>Andreas Maier (University of Cologne)</i></p>                                                                      |
| <b>12:10 – 12:30</b> | <p>38. Digital Stones, Real sweat: Estimating Building Effort from 3D Models<br/> <i>Geert Verhoeven (University of Vienna)</i>; <i>Seta Štuhec (ÖAW)</i></p>                                                                                                                                                         |

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| <b>12:30 – 13:30</b> | Lunch break                                                                                                                                                                                                                                                                                   |
| <b>13:30 – 13:50</b> | <p>331. „Spaces of an Empire“: Revisiting Space Syntax Analysis for Neo-Assyrian Palatial Architecture<br/> <i>Jannis Werner (University of Cologne)</i></p>                                                                                                                                  |
| <b>13:50 – 14:10</b> | <p>335. Towards the Algorithmic Identification of Buildings from Post Hole Locations<br/> <i>Mathys du Plessis (Nelson Mandela University)</i>; <i>Raphaëlle Javet (University of Zurich)</i>; <i>Aurèle Pignolet (InSitu Archéologie SA)</i></p>                                             |
| <b>14:10 – 14:30</b> | <p>328. 3D Models as Research Infrastructures: workflow and architectural palimpsests at the Theatre of Marcellus<br/> <i>Marika Griffio*</i>; <i>Carlo Inglese*</i>; <i>Simone Lucchetti*</i></p> <p><i>* Sapienza Università di Roma</i></p>                                                |
| <b>14:30 – 14:50</b> | <p>457. Decoding Archaeological Space: A Space Syntax Study of the Hellenistic Baths at Sicily<br/> <i>Mei Yang (UAB)</i></p>                                                                                                                                                                 |
| <b>14:50 – 15:10</b> | <p>66. Virtual Deconstruction: a Semantic Approach to reality based 3D models in Urban Archaeology<br/> <i>Matteo Lombardi*</i>; <i>Diego Ronchi*</i>; <i>Elisabetta Di Virgilio*</i>; <i>Daniele Ferdani*</i>; <i>Nicodemo Abate*</i></p> <p><i>* Consiglio Nazionale delle Ricerche</i></p> |
| <b>15:10 – 15:30</b> | <p>436. From 3D Models to VR: Multi-Scalar Viewing for Neolithic Art<br/> <i>Dana Alnafour (Tsukuba University)</i></p>                                                                                                                                                                       |

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| <b>15:30 – 16:00</b> | Coffee break                                                                                                                                                                                                                                                |
| <b>16:00 – 16:20</b> | 390. DIGital: A Substantive Virtual Field School Experience<br><i>Devin San Nicolas*</i> ; <i>Tate Whittaker*</i> ; <i>Ryan Wood*</i> ; <i>Jarom Craghead*</i> ; <i>Scott LaRocca*</i> ; <i>Kayeleigh Sharp</i><br><br><i>* Northern Arizona University</i> |
| <b>16:20 – 16:40</b> | 406. Quantifying material costs in Building Archaeology: an AI application of the Taglab tool to Massenzio's circus.<br><i>Domenica Dininno (CNR)</i> ; <i>Marco Callieri (CNR)</i>                                                                         |
| <b>16:40 – 17:00</b> | 294. Fear of the Black Box: Interpretable Machine Learning for Bulgarian Development-Led Archaeological Surveys<br><i>Nadezhda Kecheva (Bulgarian Academy of Sciences)</i>                                                                                  |
| <b>17:00 – 17:20</b> | 351. Archaeological AI in Data-Scarce Underwater Contexts: Exploring Archaeological Understanding and Machine Learning.<br><i>Benjamin King*</i> ; <i>Øyvind Ødegård*</i> ; <i>Aurora Hoel*</i><br><br><i>* NTNU Trondheim</i>                              |
| <b>17:20 – 17:30</b> | Break                                                                                                                                                                                                                                                       |
| <b>17:30 – 17:50</b> | 232. Evaluating Deep Learning for Frost Feature Classification: Integrating CNNs and Expert Knowledge in Archaeological Micromorphology<br><i>Sofia Kouki*</i> ; <i>Li Li*</i> ; <i>Vera Aldeias*</i><br><br><i>* University of Algarve</i>                 |

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| <b>17:50 – 18:10</b> | 459. A theory-guided machine learning framework for archaeological science<br><i>Vana Orfanou (Ludwig Maximilian University of Munich)</i> ; <i>Niklas Stausberg (Ludwig Maximilian University of Munich)</i>  |
| <b>18:10 – 18:30</b> | 438. Archaeology Information Modeling - Conceptualization and Pilot Study of BIM-Based 4D Excavation Database Systems<br><i>Bjarne Kortmann (BerGSAS)</i>                                                      |
| <b>18:30 – 19:00</b> | 369. Towards a Framework for Modelling Uncertainty in Archaeological Excavation Information<br><i>Natalie De Schuytener (University of Antwerp)</i>                                                            |
| <b>19:00 – 19:20</b> | 94. Multimodal Semantic Integration for Next Generation Documentation of Cultural Heritage<br><i>Changyu Chen*</i> ; <i>Martin Tomko*</i> ; <i>Kourosh Khoshelham*</i><br><br><i>* University of Melbourne</i> |
| <b>19:20 – 19:30</b> | Discussion                                                                                                                                                                                                     |

## 10. Handling the Past: Methodological Reflections on Object Interaction in Physical and XR Archaeological Contexts

*Despoina Sampatakou (University of Glasgow)*

*Andreea Caragea (University of Glasgow)*

*Ross Johnstone (University of Glasgow)*

*Iain McLean (University of Glasgow)*

*Kieran Waugh (University of Glasgow)*

*Julie Williamson (University of Glasgow)*

### Introduction

Immersive technologies, often grouped under the term XR, are increasingly utilised in archaeological and cultural heritage practices to broaden access and deepen public engagement (Hutson and Hutson, 2024). While existing research has largely focused on individual user experience, the social dynamics of group interaction, particularly object turn-taking and collaborative meaning-making, remain underexplored (Škola et al. 2020). This study investigates how small groups coordinate around cultural objects in physical and immersive virtual environments, with particular attention to turn-taking, collaborative interpretation, verbal negotiation, and perceptions of learning.

### Methods and Materials

The study employed high-quality handmade physical replicas and their one-to-one digital counterparts within a controlled laboratory setting and its immersive digital twin. Participants completed an object-centred collaborative task designed to prompt open discussion and narrative construction through archaeological storytelling (Perry et al. 2025). The sample included participants with diverse backgrounds, ranging from archaeology and heritage practitioners to individuals with no formal training in archaeology or immersive technologies.

A mixed methods approach combined quantitative interaction logging that tracked object position and duration of handling with post-session semi-structured interviews. Qualitative data were analysed using Reflexive Thematic Analysis, while quantitative analysis focused on patterns of object interaction within each condition.

### Results

Interaction logs and interviews revealed distinct behavioural patterns across conditions. In the physical conditions, participants tended to hold objects for longer periods but passed them less frequently, resulting in a lower overall proportion of time spent handling objects. In contrast, interactions in VR were characterised by shorter but more frequent handling episodes, leading to increased total interaction time and a more dynamic rhythm of turn-taking. Participants attributed this difference to a perceived sense of safety in VR, where objects could not be dropped or damaged.

Across both conditions, perceptions of authenticity emerged as central. Participants expressed trust in experiences they perceived as historically accurate and transparent, especially in the physical conditions.

Order effects further shaped engagement. Groups who encountered the physical condition first exhibited a clear anchoring bias when transitioning to VR, whereas groups who began in VR did not demonstrate the same effect.

### Discussion

The findings demonstrate that XR environments can support meaningful learning and collaborative engagement with cultural heritage objects, even when physical materiality is absent. While physical replicas foster tactile empathy and material authenticity, immersive virtual environments afford alternative modes of exploration that encourage frequent interaction, shared interpretation, and narrative exchange.

Methodologically, the study advances a holistic framework for examining social engagement in digital archaeology by integrating computational tracking with systematic qualitative analysis. The results highlight the analytical value



of narrative responses and interaction metrics, such as object position, in understanding how people interact with and collaborate around cultural objects. These insights can inform the design and evaluation of future immersive cultural heritage experiences, particularly those aiming to balance engagement, authenticity, and interpretive transparency.

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## 25. Potential dwelling structures of the Upper Palaeolithic in Western, Central, and Eastern Europe: A computer-aided quantitative analysis

*Dennis Batz (University of Cologne)*

*Andreas Maier (University of Cologne)*

Today, architectural structures for shelter and dwelling are a ubiquitous phenomenon in human societies. While the earliest potential evidence for built dwelling structures predates the Upper Palaeolithic, it is during this

timeframe – particularly from the mid to late Upper Palaeolithic onwards – that archaeologists seem to document these structures more frequently. In Western and Central Europe, sites like Gönnersdorf display features interpreted as remnants of former tent-like structures (Sensburg/Moseler 2008). In Eastern Europe, sites like Dolni Vestonice, Pavlov, and Mezhirich are well known for their mammoth bone structures (Iakovleva 2015), but their interpretation as dwellings is controversial. Equally, tent-like structures and their reconstructions are not without controversy either.

Furthermore, a dichotomy is suggested by the distribution of tent-like structures primarily identified in Western and Central Europe and mammoth-bone structures exclusively in Eastern Europe (see Fig. 1). Whether this observation reflects divergent dwelling traditions of Late Pleistocene hunter-gatherers, or whether these features represent remnants of non-analogue constructions remains an open question.

To contribute to this debate, we present the results of a master's thesis that quantitatively compares the size and layout of structures interpreted (at least by some authors) as the remains of dwellings. The comparison involves the sizes and shapes of the structures, as well as features such as hearths, pits, or stone settings. Where possible, available 14C-data for each structure was recorded. Finally, the respective dating of each site and its geographical position – focusing on the longitudinal position – is recorded and used as an attribute for comparison. The underlying database compiled for the study lists 139 structures from 55 sites. All data are exclusively based on previously published and publicly accessible sources, with sites distributed across Western, Central, and Eastern Europe.

However, not all sites were suitable for the quantitative analysis because of strict requirements regarding the dating quality, and plausibility of reconstruction to guarantee that meaningful data are processed and produced. Eventually, 50 structures from 31 sites passed the evaluation using a predefined set of criteria.

Only structures for which an outline drawing exists – or could be generated based on the available data – were considered. The outlines were processed using semi-automated program code PyREnArA (Python-R-Environment for

Artifact Analysis) (John et al. 2023), which requires a specific input format. For the outline reconstruction, the outer edge of the published drawing was used. For structures with complete outlines but no available drawing, the outline was manually generated. All structures were oriented north before further processing.

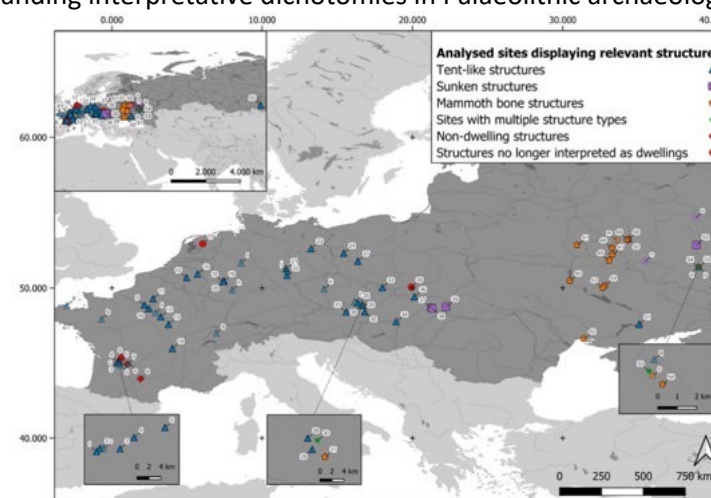
After the processing of the outlines – and the collection of further structural data – multiple statistical methods – including tests for significance, coefficient of variation, principal component analysis, and redundancy analysis – were applied to test for significant differences between structural types and for diachronic or spatial trends.

With few exceptions, the two structure types – tent-like and mammoth bone structures – display strong overlap in their quantitative properties and do not show statistically significant morphological or structural differences. This applies to all tested metrics and structural elements, suggesting similar architectural principles. Only the floor area exhibited a significant difference, with mammoth bone structures tending to be larger and more compact. The similarity between mammoth bone and tent-like structures indicates that both may have served comparable domestic or residential functions. The larger dimensions of mammoth bone dwellings likely reflect their more permanent nature rather than different cultural or functional roles. The spatial distribution of mammoth bone structures and tent-like structures is already established in research. However, the chronological and spatial distributions of the analysed structures additionally show a distinct pattern, displaying multiple regional shifts – especially from the Epigravettian onwards.

Given that both structure types follow similar morphological and structural principles, it is plausible that we are observing variations of a shared architectural logic. The distinct spatial separation between the two types could be explained in two ways: (1) it might represent a real cultural divergence in construction traditions, or (2) it could reflect a research-historical and methodological bias resulting from divergent excavation and reconstruction practices in Western versus Eastern Europe. The observed regional shifts during certain periods are still in need of explanation and further research –

whether this pattern is based on a historical-archaeological reality or rather research history – remains a desideratum for now.

This study demonstrates the potential of quantitative digital methods to test long-standing interpretative dichotomies in Palaeolithic archaeology.



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### 38. Digital Stones, Real sweat: Estimating Building Effort from 3D Models

*Geert Verhoeven (University of Vienna)*

*Seta Štuhec (ÖAW)*

#### Introduction

In Slovenia's Karst region, over 150 small dry-stone shepherd shelters remain from nineteenth- and early-twentieth-century pastoral life. While image-based 3D documentation of such structures is now routine, their analytical potential is rarely explored.

This presentation examines whether digital 3D surface models can act as quantitative proxies for architectural energetics: the labour and energy required to build them. By translating geometric properties of cleaned, segmented 3D models into biomechanical and physiological parameters, it links photogrammetry with human energetics to estimate the temporal and metabolic costs of constructing these shelters, and to assess the assumptions and interpretative limits of such estimates.

#### Materials and Methods

##### Image acquisition and 3D surface modelling

22 dry-stone shepherd shelters, many hidden in forested terrain, were documented using dense networks of overlapping photographs acquired with various D-SLR Nikon cameras (sometimes mounted on a telescopic pole for roof coverage or with on-camera LED lighting for the small interiors).

The imagery was processed in Agisoft PhotoScan Professional to yield dense triangular 3D meshes. These were scaled via distances measured between coded targets and oriented with compass readings and box levels visible in the 3D models. Mesh cleaning, removal of vegetation and box levels, hole filling, and decimation were performed in Geomagic Studio 2013 and Atango Balancer nPro to produce watertight, two-manifold surfaces with ~2 mm geometric tolerance.

#### Deriving geometric and physical quantities

The total enclosed volume was derived from these closed 3D surfaces. To approximate the actual stone material, 30 % of this volume was subtracted to account for voids between irregular stones, following published estimates. Representative limestone samples from the same area provided an average density of  $2718 \text{ kg m}^{-3}$ , a number derived from weighing and volume estimations (via 3D models) of various stones. Multiplying the total stone volume by this stone density yielded each shelter's total stone mass.

#### Deriving labour time

An average stone mass of 5 kg was assumed. Dividing the total stone mass by this value gave the approximate number of stones per shelter. Timed experimental trials indicated about 30 s to select, lift, and place a stone from the abundantly nearby material (any potential cost related to finding and fetching the stones is thus not part of these quantifications). Assuming 8-hour working days, the total stone handling time was converted into person-days of labour.

#### Estimating metabolic cost

To estimate the metabolic or caloric construction cost, a biomechanical model was developed that accounted for two components of mechanical work:

1. External work: the effort to lift the total stone mass vertically to the structure's Centre of Mass (CoM);
2. Internal work: the effort of repeatedly raising and lowering the builder's body during each lift.

The total lifting work was computed as:

$$\begin{aligned}
W_{\text{total\_work\_lifting}} &= W_{\text{upward\_phase}} + W_{\text{downward\_phase}} = \\
&W_{\text{lifting\_stones}} + W_{\text{lifting\_body}} + W_{\text{lowering\_body}} = \\
&W_{\text{lifting\_stones}} + 1.3W_{\text{lifting\_body}} = \\
N_{\text{stones}} (9.81 \text{ m/s}^2) ((5 \text{ kg}) (h_{\text{CoM\_shelter}} + 0.15 \text{ m}) + 1.3 (65 \text{ kg}) (0.3 \text{ m}))
\end{aligned}$$

where 9.81 ms<sup>-2</sup> is the gravitational acceleration, 5 kg the mean stone mass, hCoM\_shelter the shelter's CoM, 0.15 m to account for lifting each stone slightly above its deposition height, 65 kg the assumed mean body mass, 0.3 m the body's vertical CoM displacement of a 1.7 m tall person in a stoop lift (i.e., straight legs and bent back), and 1.3 to account for the added metabolic cost of lowering the body (≈30 % of the body raising cost). The resulting mechanical work was then doubled to include stone repositioning and handling. The total physiological energy demand was then derived from W<sub>total\_work\_lifting</sub> using an assumed muscular efficiency of 20 % and a joules to kilocalories conversion (1 kcal = 4.184 kJ):

$$E_{\text{food}} = \frac{2W_{\text{total\_work\_lifting}}}{\frac{4184 \text{ J}}{\text{kcal}} \eta},$$

with E<sub>food</sub> being the energy content (in kcal) of the food that a shepherd must consume to fuel his body for shelter building.

## Results

The figure tabulates all shelter-specific data and variable values. The computed total lifting work ranged from 95 kJ to 4945 kJ per shelter, equivalent to caloric expenditures of 226 kcal to 11818 kcal. Divided by the number of building days, this implies a mean additional energy demand of about 660

kcal per day, which raises a shepherd's total daily energy expenditure from roughly 2200 kcal for sedentary activity to about 2860 kcal, which is equivalent to a moderately active individual.

These values suggest that shelter construction was metabolically modest: a physically sustainable task rather than an extreme labour episode. Larger shelters were likely built collaboratively, further reducing individual daily effort.

| Shelter ID                                     | Height CoM [m] | Volume [m <sup>3</sup> ] | Stone volume [m <sup>3</sup> ] | Stone mass [metric ton] | Number of stones | Building time [hours] | Building time [days] | Work lifting stones [kJ] | Work lifting body [kJ] | Work upward phase [kJ] | Work downward phase [kJ] | Total work of lifting [kJ] | Total building work [kJ] | Caloric cost of building [kcal] | Extra daily caloric expenditure [kcal] |
|------------------------------------------------|----------------|--------------------------|--------------------------------|-------------------------|------------------|-----------------------|----------------------|--------------------------|------------------------|------------------------|--------------------------|----------------------------|--------------------------|---------------------------------|----------------------------------------|
| A05_001                                        | 0.880          | 11.8                     | 8.2                            | 22.4                    | 447              | 37.3                  | 4.7                  | 276                      | 806                    | 1082                   | 257                      | 1338                       | 1077                     | 2599                            | 667                                    |
| A05_002                                        |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| A05_003                                        | 0.836          | 35.3                     | 25.3                           | 63.4                    | 12578            | 305.6                 | 37.7                 | 613                      | 2422                   | 3038                   | 738                      | 3766                       | 2530                     | 9081                            | 682                                    |
| A05_004                                        | 0.538          | 9.2                      | 2.3                            | 6.2                     | 1233             | 10.3                  | 1.3                  | 40                       | 236                    | 276                    | 71                       | 387                        | 604                      | 829                             | 646                                    |
| A05_005                                        | 0.454          | 3.4                      | 2.4                            | 6.4                     | 1279             | 10.7                  | 1.3                  | 38                       | 245                    | 283                    | 73                       | 356                        | 732                      | 851                             | 639                                    |
| A05_006                                        | 0.444          | 2.7                      | 1.9                            | 5.2                     | 1040             | 8.7                   | 1.1                  | 30                       | 200                    | 231                    | 60                       | 291                        | 581                      | 684                             | 637                                    |
| A05_007                                        | 0.430          | 4.5                      | 2.8                            | 7.7                     | 1547             | 12.9                  | 1.6                  | 43                       | 296                    | 339                    | 89                       | 428                        | 856                      | 1023                            | 825                                    |
| A05_008                                        | -              | -                        | -                              | -                       | -                | -                     | -                    | -                        | -                      | -                      | -                        | -                          | -                        | -                               | -                                      |
| A05_009                                        | 0.766          | 0.8                      | 0.6                            | 1.6                     | 322              | 2.7                   | 0.3                  | 14                       | 62                     | 76                     | 18                       | 95                         | 189                      | 226                             | 674                                    |
| A05_010                                        |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| A05_011                                        | 0.688          | 2.7                      | 1.9                            | 5.1                     | 1010             | 8.4                   | 1.1                  | 42                       | 193                    | 235                    | 58                       | 293                        | 586                      | 700                             | 605                                    |
| A05_012                                        | 0.618          | 3.6                      | 2.5                            | 6.8                     | 1369             | 13.4                  | 1.4                  | 52                       | 262                    | 313                    | 79                       | 392                        | 784                      | 937                             | 657                                    |
| A05_014                                        | 0.700          | 5.5                      | 3.8                            | 95.4                    | 2086             | 17.4                  | 2.2                  | 88                       | 899                    | 482                    | 120                      | 1607                       | 1215                     | 3852                            | 667                                    |
| A05_014                                        | 0.886          | 3.7                      | 2.6                            | 7.1                     | 1410             | 11.8                  | 1.5                  | 38                       | 230                    | 268                    | 81                       | 409                        | 817                      | 977                             | 665                                    |
| A05_015                                        | 0.827          | 4.2                      | 2.9                            | 8.0                     | 1593             | 13.3                  | 1.7                  | 76                       | 305                    | 381                    | 91                       | 473                        | 945                      | 1176                            | 680                                    |
| A05_016                                        | 0.632          | 2.9                      | 1.4                            | 3.9                     | 779              | 6.5                   | 0.8                  | 30                       | 149                    | 179                    | 45                       | 224                        | 447                      | 535                             | 629                                    |
| A05_017                                        | 0.602          | 3.8                      | 2.5                            | 6.8                     | 1356             | 11.3                  | 1.4                  | 50                       | 239                    | 309                    | 78                       | 387                        | 774                      | 925                             | 655                                    |
| A05_018                                        | 0.579          | 1.4                      | 0.9                            | 2.6                     | 514              | 4.1                   | 0.5                  | 18                       | 98                     | 117                    | 29                       | 146                        | 292                      | 349                             | 633                                    |
| A05_019                                        | 0.920          | 43.2                     | 30.3                           | 82.2                    | 16444            | 137.0                 | 17.4                 | 820                      | 3166                   | 4001                   | 944                      | 4945                       | 3880                     | 11818                           | 680                                    |
| A05_019                                        | 0.862          | 16.1                     | 11.3                           | 30.6                    | 6127             | 51.1                  | 6.4                  | 306                      | 1172                   | 1436                   | 352                      | 1828                       | 1605                     | 4368                            | 648                                    |
| A05_043                                        | 0.712          | 10.1                     | 11.5                           | 30.7                    | 6143             | 51.2                  | 6.4                  | 300                      | 1175                   | 1434                   | 352                      | 1767                       | 1573                     | 4270                            | 648                                    |
| A05_0513                                       | 0.713          | 1.9                      | 2.7                            | 7.4                     | 1475             | 12.3                  | 1.5                  | 42                       | 282                    | 349                    | 85                       | 429                        | 857                      | 1024                            | 648                                    |
| average                                        | 0.677          | 8.7                      | 6.1                            | 16.5                    | 3310             | 27.4                  | 3.4                  | 118                      | 638                    | 786                    | 189                      | 876                        | 1882                     | 2382                            | 664                                    |
| Gravitational acceleration [m/s <sup>2</sup> ] |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Volume [m <sup>3</sup> ]                       |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Mass density stone [kg/m <sup>3</sup> ]        |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Efficiency [%]                                 |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Average mass stone [kg]                        |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Handling time per stone [s]                    |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Daily hours of labour [h]                      |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Height above disposition [m]                   |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Body mass shepherd [kg]                        |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| CoM displacement 1.7 m shepherd [m]            |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Proportion negative vs positive work           |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |
| Total work multiplier                          |                |                          |                                |                         |                  |                       |                      |                          |                        |                        |                          |                            |                          |                                 |                                        |

## Discussion

### Assumptions and simplifications

The biomechanical model reduces human movement to vertical lifting, excluding translational, kinetic or environmental factors. Still, it suffices for order-of-magnitude estimates. Including kinetic energy would change total work by only about 2 %, which is less than the 3D modelling uncertainties.

### Implications for archaeological energetics

This work shows that image-based 3D documentation can inform quantitative analyses of human effort, traditionally based on experimental building or ethnographic analogy. By coupling surface geometry with basic physical principles, archaeological 3D data gain interpretative depth beyond visualisation.

## Conclusion

Geometrically accurate 3D models can support physically meaningful reconstructions of past labour. Estimating building effort from digital surfaces enables replicable, data-driven insights into the human cost of vernacular architecture. Despite remaining uncertainties, integrating biomechanics and physiology points toward a computational archaeology where digital models reveal not just heritage surfaces but also the embodied energy behind them.

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## 66. Virtual Deconstruction: a Semantic Approach to reality based 3D models in Urban Archaeology

*Matteo Lombardi (Consiglio Nazionale delle Ricerche)*

*Diego Ronchi (Consiglio Nazionale delle Ricerche)*

*Elisabetta Di Virgilio (Consiglio Nazionale delle Ricerche)*

*Daniele Ferdani (Consiglio Nazionale delle Ricerche)*

*Nicodemo Abate (Consiglio Nazionale delle Ricerche)*

## Introduction

The bombing raids on Terracina in September 1943 caused considerable destruction in the area now known as Piazza del Municipio. Unexpectedly, however, they marked the beginning of a new chapter in the city's history. The collapse and demolition of the buildings exposed the perfectly preserved remains of the Roman city below. This discovery initiated a long process of archaeological excavation that covered a large part of the city from the 1990s onwards.

Among the most remarkable finds are the porticus and the theatre complex, whose restoration was completed in 2023 and which is now the focus of the Foro Emiliano Project (FEP). This project was initiated by SABAP Lazio and the CNR-ISPC as a result of the recent excavations and restoration of Terracina's Roman theatre.

The Project primarily aims to document, analyse and disseminate the archaeological heritage of Terracina's historical centre. Therefore, starting from the three-dimensional documentation of a multi-layered urban area, the project carries out a historical investigation and a diachronic analysis of the city. This includes the study of excavation materials, the performance of a virtual "deconstruction", the analysis of historical and archaeological structures and the creation of one - or several - 3D simulations.

Beyond historical analysis, the project aims to develop a new knowledge model for an urban area with continuous life. This model integrates scientific research, urban development and management, and public dissemination

through a technical and methodological framework based on transparency of sources.

### Methods and Materials

The relationship between the different layers of the city of Terracina makes the case-study particularly complex. The modern buildings enclose the monumental remains of the ancient city, resting on them and interacting with them in unique and varied ways.

Consequently, digitisation consisted of the implementation of several measurement paradigms. This initial step was completed by integrating different technologies: static (TLS) and mobile (SLAM) laser scanning, aerial and terrestrial photogrammetry and spherical videogrammetry. This approach made it possible to tackle the complexity of a case study characterised by extensive spatial coverage and the constant challenge of an urban canyon. The complete coverage of the city was achieved by combining 220 laser scans, 3000 drone images, 1.500 terrestrial pictures and several hours of video recordings, both in single frames and in spherical form.

A semantic model was then created by segmenting the reality based geometries. This process enabled the analysis of the wall stratigraphy of the theatre and porticus complex and thus the virtual deconstruction of the context on the basis of the archaeological analysis. The segmentation process was carried out using the native tools of the 3D modelling software Blender and the Extended Matrix Framework (EMF).

The development of the CNR IPSC's EMF has triggered a profound methodological shift towards transparent information modelling processes. Moreover, the framework is mainly based on open source solutions. This system gives the user the ability to create a personalised workflow, promoting adaptability, data sharing and reuse. The central pillar of this framework is the EM tools: an open-source plugin for Blender. The plugin itself acts as a link between Blender and the Extended Matrix, a formal, node-based language that embodies the Matrix archaeological stratigraphic approach. This language is expressed via semantic graphs through the open source software

yEd. Thus, each geometry is given a set of data and features as well as a chronological relationship to the other geometries as expressed in the graph. It is possible to interact visually with the geometric representations of the data, such as the proxies, and/or directly consult sources and information at different levels of detail. The system not only improves the reuse and readability of data, but also promotes multidisciplinary collaboration and data granularity. In practice, it allows professionals from different fields, including those without an archaeological background, to visualise archaeological data at different levels, down to the raw data. This workflow enables a documented reconstruction process that can be shared and fully inspected locally or online via EMviq. This tool, still within the EMF, is based on the ATON framework and enables interactive online cross-device querying and 4D visualisation of 3D models and their extended matrices.

### Results

The final product consists of the superimposition of two three-dimensional models: a reality-based model and a deconstructive model that illustrates the traces of the development processes of the structures. The latter forms the backbone of the project: it is not a static and visually appealing virtual reconstruction, but a dynamic, data-enriched management model. Both models can be navigated and queried via the ATON web app.

In addition, the proxy geometries are linked to a graph DB. This DB contains stratigraphic and chronological relationships that allow the reconstruction of the development phases of the monuments. In addition, this system has advanced filtering functions (e.g. by chronology) that enable real-time deconstruction of the urban structure. For example, all Roman buildings from the 1st century AD can be easily isolated from the rest of the city.



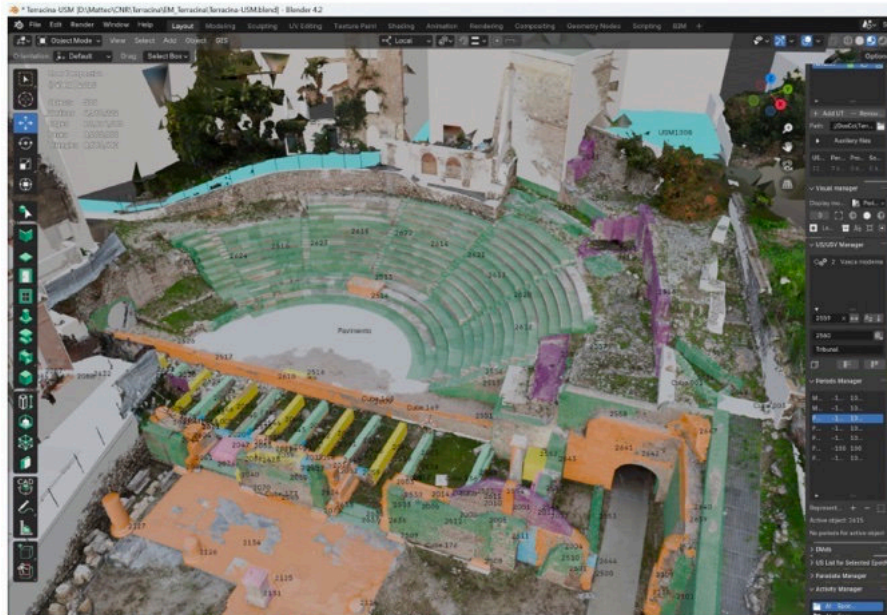


Figure 1: Proxy and Reality Based model

## Discussion

This model describes a new methodological approach for multistratified urban scenarios. This workflow considers 3D models as dynamic 3D databases with the possibility to develop a new semantic approach for cultural heritage models towards Niccolucci's Heritage Digital Twin system.

The EM tools, together with the whole pipeline, represent an extraordinary tool for archaeological research whose full potential has yet to be realised. It undoubtedly represents a major step forward in archaeological information modelling and constitutes a solid multidisciplinary bridge between professionals. The workflow stimulates an integrable semantic modelling process that can be constantly updated and enriched by different professionals alongside research or project progress. Thus, the semantic 3D model becomes both a 3D database and a fulcrum of the heuristic process, without sacrificing management and technical capabilities.

Furthermore, the paper emphasises that 3D survey data should not be managed as a final product, but should be considered as raw data and therefore integrated into a broader heuristic and analytical process. The system allows the integration of models created for different purposes: the RB, the proxy model and the reconstruction are thus deeply intertwined.

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## 94. Multimodal Semantic Integration for Next Generation Documentation of Cultural Heritage

Changyu Chen (University of Melbourne)

Martin Tomko (University of Melbourne)

Kourosh Khoshelham (University of Melbourne)

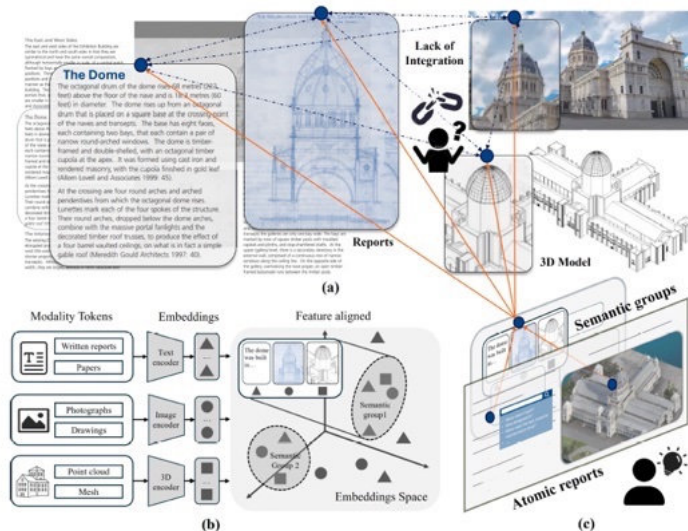


Figure 1: Illustration of multimodal fragmentation to semantic integration. (a) Multimodal records lacking integration. (b) Semantic grouping and alignment. (c) Atomic reports as semantic interfaces for integrated documentation.

### Introduction:

The evolution of cultural heritage documentation has seen a significant transformation over the past decades, changing how heritage is recorded and interpreted. Early documentation relied on drawings, sketches, and field notes to convey spatial information. With the advent of computer technologies in the late 20th century, virtual archaeology emerged as a new paradigm. Three-dimensional reconstruction technologies, such as

photogrammetry and laser scanning, shifted heritage records from illustrative descriptions toward geometric accuracy, enabling the capture of details once difficult to preserve.

Technological expansion has, however, also resulted in heritage knowledge becoming fragmented across different and poorly linked modalities, including narrative reports, photographic records, and 3D models. While each captures complementary dimensions of information, they are often treated as disjointed entities, which complicates integration and limits interpretation. In this context, we envision an incremental transformation of cultural heritage information exchange, which is still grounded in the report as its core medium, maintaining the role of the author in leading the reader, but modernized in its delivery and capabilities supporting alternative reading pathways. The next generation of documentation should move beyond static archival storage toward multimodal semantic integration.

This study focuses on documentation describing physical heritage sites at the building or site scale, characterized by clear spatial evidence. It primarily includes historical, archaeological, and condition reports that describe site elements. Reports centered solely on single movable artifacts, such as pottery, furniture, or other fragments, are excluded unless they directly contribute to site-level interpretation.

### Envisioning semantically integrated multimodal documentation:

Transforming raw records into integrated documentation requires reconciling differences in data transmission, meaning, and understanding. To better understand these challenges and how they are being addressed in an increasingly multimodal environment, we introduce a conceptual framework of three forms of interoperability, which are conceptually independent but mutually reinforcing.

Technical interoperability concerns the compatibility and exchange of data across different platforms. Many initiatives, such as Europeana and the Archaeology Data Service (ADS), have developed standards and protocols for

data sharing. These solutions for 3D data are often highly specialized and operate in isolation.

Semantic interoperability focuses on the consistent interpretation of information, enabling machines and humans to understand what that data means—for example, recognizing that a wall plan represents a wall, not just two parallel lines. It forms the semantic bridge between the technical and experiential layers, enabling meaningful communication between systems and users. Research using ontologies and linked open data has improved how information can be connected and reused. The next step requires cross-modal semantic alignment, creating a shared semantic space that enables meaningful integration of data.

Experiential interoperability addresses how data is understood by diverse stakeholders. Heritage records are inherently interpretive rather than purely descriptive. Research in visualization, reasoning, and interactive retrieval has explored methods to help diverse audiences engage with information. Currently, multimodality naturally reflects multiple perspectives on the same object, bringing potential for adaptive and personalized representations that can respond to individual user needs.

Building on the semantic bridge that supports meaningful multimodal integration, we propose the concept of atomic reports as a practical interface linking textual, visual, and spatial data. Rather than fully replacing traditional storage formats, atomic reports enrich them with semantic connections that support cross-modal linking and navigation. These reports remain based on the narrative structure but introduce semantic annotations at key points, each connected to predefined semantic groups representing corresponding entities across modalities and dynamically accessible through APIs. In this way, a report can still be read as the author intended but also serve as an entry to other related information, allowing readers to interpret and analyze it as they intend. The report shifts from being a static end product to a dynamic mediator between human interpretation and machine reasoning, forming an interactive and retrievable semantic interface.

Achieving this vision requires robust semantic alignment, ensuring that entities mentioned in the report, such as a specific window or stratigraphic layer,

can be consistently identified and linked to their counterparts in images or 3D models. On the textual side, natural language processing methods extract and normalize entities, merging duplicates and grouping sentences that refer to the same specific object. Ontology-based frameworks organize these groups within a structured semantic model, providing persistent identifiers to maintain continuity across modalities. Additionally, modeling spatial relations and geometric dependencies extends this alignment to the visual domain, where context-aware visual grounding, segmentation, and component reconstruction enable the integration of geometry with semantics.

Implications and applications:

It is foreseeable that enhanced semantic interoperability will build on the foundation of technical interoperability, which enables data to be accessed without dependence on specialized software environments. It will also expand the possibilities of experiential interoperability, allowing new and reliable forms of multimodal visualization, retrieval, and adaptive interaction that respect differences in expertise and intent.

In short, our framework provides a methodological foundation for integrating human-readable narratives with machine-actionable semantics, contributing to the understanding of how computational methods reshape the interpretation, analysis, and reuse of cultural heritage knowledge.

## 134. Design and Evaluation of a Low-Cost IoT Wireless Sensor Network for Environmental and Behavioural Monitoring in Cultural Heritage Structures and Collections

*Juan Palomeque-Gonzalez (IDEA- Madrid)*

Design and Evaluation of a Low-Cost IoT Wireless Sensor Network for Environmental and Behavioural Monitoring in Cultural Heritage Structures and Collections

### Introduction

Continuous environmental monitoring and visitor-behaviour analysis are critical for mitigating the deterioration of cultural heritage structures. Temperature, humidity, vibration, and human presence directly influence material conservation, yet commercial monitoring systems remain prohibitively expensive, proprietary, and difficult to adapt to the specific needs of museums and historical buildings.

This study explores the feasibility of designing a low-cost, modular IoT system using off-the-shelf microcontrollers, open-source firmware, and cloud-based data services. The project investigated whether a complete, reproducible pipeline—from wireless sensor network (WSN) to cloud dashboard—can be achieved with minimal resources, enabling heritage professionals worldwide to deploy scalable monitoring infrastructures.

### Methods and Materials

The prototype was conceived as a three-tier architecture comprising:

- Wireless Sensor Network (WSN):

Built around ESP32 microcontroller units (MCUs), each node integrated sensors for temperature (DHT22), humidity, sound, vibration, and motion (PIR and ultrasonic). Nodes communicated through Bluetooth Low Energy (BLE) to minimize power consumption.

- Computing Hub (CH):

A Raspberry Pi served as the intermediary between the WSN and the cloud. It received sensor data, executed edge computing routines (event classification, local logging, and visualisation), and relayed structured records to remote storage.

- Cloud Backend:

Developed with Microsoft Azure services. Sensor data were archived in blob storage, processed in a relational SQL database, and visualised through a Streamlit-based dashboard providing real-time feedback, temporal queries, and performance metrics.

A modular firmware architecture allowed interchangeable nodes and straightforward integration of additional sensors. Communication reliability and latency were tested under different transmission intervals and distances.

### Results

- WSN Performance:

The wireless sensor network (WSN) was able to record environmental variables such as temperature, humidity, presence, movement, sound, and visitor distance in a reliable and autonomous way, using low-cost ESP32 microcontrollers and off-the-shelf sensors such as the DHT22.

- Computing Hub and Cloud Integration:

The computing hub successfully aggregated readings, performed event classification, and uploaded structured data to the Azure backend in near real-time. The Streamlit dashboard provided interactive graphs of environmental variables and event logs, confirming the system's ability to support remote and local monitoring simultaneously.

- Image Analysis:

Among the models tested, CLIP demonstrated the most consistent performance in detecting the presence or absence of people in still images, validating the potential of zero-shot models for lightweight behavioural analytics without large, domain-specific datasets.

#### Discussion

The results confirmed that low-cost, general-purpose components can provide reliable environmental and behavioural monitoring suitable for preventive conservation tasks. Compared to high-end heritage monitoring platforms, this open prototype offers several advantages.

**Affordability and Accessibility:** The entire system—including sensors, MCUs, hub, and cloud services—was assembled for under £150, demonstrating feasibility for small institutions and research teams in resource-constrained contexts.

**Modularity and Reproducibility:** Each subsystem can be independently replicated or improved. The use of open-source code and public documentation promotes transparency and encourages community-driven extensions, following FAIR (Findable, Accessible, Interoperable, Reusable) data principles.

**Integration of Edge and Cloud Computing:** Combining local processing with cloud-based analytics proved effective in reducing latency and data transfer costs while maintaining remote accessibility—an essential feature for heritage sites with intermittent connectivity.

#### Conclusions and Wider Implications

This research demonstrates that affordable, modular IoT systems built from open hardware and open-source software can deliver reliable and reproducible environmental and behavioural monitoring for the conservation of cultural heritage structures. The prototype validates a scalable and transparent approach to data acquisition and analysis that bridges the gap between experimental digital heritage research and practical heritage management.

Beyond the technical success of the prototype, the project highlights three wider implications.

**Democratisation of Heritage Technology:** The ability to assemble a complete, cloud-integrated monitoring system for under £150 enables small museums and local heritage organisations to adopt evidence-based preventive conservation strategies.

**Advancement of FAIR and Open Science Practices:** By openly documenting hardware schematics, firmware, and workflows, the system contributes to Findable, Accessible, Interoperable and Reusable (FAIR) research infrastructures and aligns with initiatives such as ARIADNE and NFDI4Objects.

**Integration of AI for Decision Support:** The inclusion of zero-shot computer vision models illustrates the potential for AI-assisted interpretation of environmental and occupancy data, enabling early detection of risk conditions or anomalous behaviour in heritage spaces.

The study thus provides both a technical demonstrator and a methodological reference model for low-cost digital heritage monitoring. It emphasises that sustainable preservation is best achieved through accessible, interoperable, and transparent digital tools that empower conservators and researchers alike.

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## 232. Evaluating Deep Learning for Frost Feature Classification: Integrating CNNs and Expert Knowledge in Archaeological Micromorphology

*Sofia Kouki (University of Algarve)*

*Li Li (University of Algarve)*

*Vera Aldeias (University of Algarve)*

### Introduction

The analysis of soil micromorphology is an essential tool in archaeology, providing insights into site formation processes and past environmental conditions (Karkanias and Goldberg 2018). Despite its analytical power, the method remains labor-intensive, time-consuming, and highly dependent on expert interpretation. Subtle or variably expressed features often lead to persistent inter-observer variability, reducing reproducibility and hindering the development of large, comparable datasets (Shahack-Gross 2016). These challenges are particularly acute for frost-affected sediments. Freeze-thaw cycles generate diagnostic microscopic signatures such as granular, blocky, and platy-lenticular microstructures, crucial for reconstructing past climates and understanding hominin adaptations to glacial environments (Vliet-Lanoë 2010).

Frost-related features can, however, overlap with those produced from other sedimentary or post-depositional processes, making consistent identification challenging—even for experienced specialists. This study addresses this gap by testing whether the convolutional neural networks (CNNs) can improve the reproducibility and interpretability of frost-related feature identification and classification in archaeological thin section images. We aim to: (1) assess the reliability of CNN-based classification across different model architectures, (2) quantify the inter-expert variability in frost feature classification and its impact on model training, (3) compare expert and machine performance on a deliberately selected sample of challenging images, and

(4) evaluate whether CNN decision-making aligns with established micromorphological criteria through interpretative analysis.

### Materials and Methods

Towards these aims, we developed a two-stage image classification framework. First, photomicrographs were binarily classified as either Frost or Non-Frost based on the presence or absence of frost-related features. Second, Frost images were further classified into three microstructural types following the established micromorphological criteria: Blocky, Granular, and Platy-Lenticular.

We analyzed 154 thin sections from eleven Plio-Pleistocene archaeological sites across Europe, the Levant, and Africa, and acquired standardized photomicrographs using a stereomicroscope under plain-polarized light with a 5x magnification. Images were cropped to isolate diagnostic features and resized to 512 × 512 pixels.

We tested five CNN architectures: three pretrained models (MobileNetV2, EfficientNetV2B0, ResNet50) leveraging transfer learning from ImageNet and fine-tuned on our dataset, a custom CNN, and a Bayesian Neural Network (BNN) implementing Monte Carlo dropout for uncertainty estimation. Training employed 5-fold cross-validation with independent test set evaluation (70/15/15% split). Performance was assessed using accuracy, precision, recall, F1-score, and confusion matrices. Score Class Activation Mapping (Score-CAM) visualized which image regions influenced model decisions, enabling qualitative comparisons with expert diagnostic features.

To quantify inter-expert variability, we conducted a blind online survey among practicing micromorphologists (19 participants with varying frost-specific experience). Participants classified 23 deliberately selected challenging images with ambiguous or poorly defined frost features, using the same two-stage scheme. Inter-expert agreement was assessed using Fleiss' and Cohen's Kappa statistics. Model-expert comparison examined shared error patterns and agreement levels.

### Results



All models demonstrated strong binary (Frost or Non-Frost) classification performance (93.7–98.7% accuracy), with EfficientNetV2B0 ( $98.7\% \pm 0.8\%$ ) and MobileNetV2 ( $98.5\% \pm 1.4\%$ ) achieving the highest scores. Multiclass classification (Blocky vs. Granular vs. Platy-Lenticular) proved more challenging, reflecting the smaller dataset size and inherent feature ambiguity. MobileNetV2 achieved the highest cross-validation performance ( $96.2\% \pm 3.3\%$ ), with all models performing well on independent test sets (95–97% accuracy). Granular structures were consistently well-classified (>95% precision/recall), while blocky and platy-lenticular classes were underrepresented and showed more frequent mutual confusion. BNN successfully flagged ambiguous cases through elevated uncertainty metrics in both tasks.

The expert survey revealed only slight overall agreement (Fleiss'  $\kappa = 0.21$ ) and highly variable individual performance (Cohen's  $\kappa = 0.02$ – $0.62$ ). Unexpectedly, intermediate-experience participants showed higher agreement (median  $\kappa = 0.45$ ) than both novices ( $\kappa = 0.20$ ) and highly experienced specialists ( $\kappa = 0.17$ ).

Score-CAM analysis revealed architecture-dependent attention patterns. Pretrained models showed spatially scattered activations with limited alignment to diagnostic criteria, often focusing on spurious correlations. In contrast, BNN and custom CNN demonstrated more interpretable patterns, focusing on frost-related porosity and sediment arrangement, features recognized by micromorphologists as diagnostic.

Direct comparison between the experts and models showed that both struggled with the same images, particularly those with poorly defined features, transitional microstructures, or features of limited spatial extent.

## Discussion

Our results demonstrate that CNNs can reliably identify and classify frost features while also quantifying prediction uncertainty. Pretrained models achieved the highest performance through transfer learning, leveraging features from large-scale datasets like ImageNet. Custom CNN and BNN, designed from scratch with limited data, showed relatively lower cross-validation performance but demonstrated crucial interpretability advantages.

However, high accuracy does not guarantee meaningful classification. Score-CAM analysis revealed a critical paradox: despite better accuracy, pretrained models failed to align with micromorphological diagnostic criteria, achieving performance through spurious correlations like background textures or lighting variations. BNN and custom CNN focused on micromorphologically relevant features (frost-related porosity and aggregate arrangement) demonstrating that accuracy alone is insufficient. This raises an important point: if models struggle to identify diagnostic features, experts face similar difficulties, as reflected in the low inter-rater agreement.

This variability is due to multiple factors. First, frost signatures exist on a continuum and can be subtle, poorly developed, or overlap with other processes (Vliet-Lanoë, 2010). Second, we deliberately selected the most ambiguous images of our dataset for the expert survey, and reduced dynamic analytical practice to static, cropped images at fixed magnification lacking stratigraphic context, inevitably increasing the disagreement. Crucially, experts and models struggled with the same images: those with transitional features, poorly developed signatures, dense packing, or limited spatial extent. This convergence validates that difficulty often lies in inherent feature ambiguity rather than classifier or expert knowledge. Some images simply contain insufficient diagnostic information for definitive classification. BNN's uncertainty quantification successfully flagged these genuinely ambiguous cases, providing valuable confidence information. Rather than indicating failure, low agreement reveals that both experts and models respond similarly to the inherent ambiguity of the data.

Given these strengths and shared limitations, deep learning emerges as a complementary tool in archaeological micromorphology. This human-in-the-loop workflow, where models provide the initial classification and flag ambiguous cases, addresses micromorphology challenges of time intensity, inter-observer variability, and scalability. While limitations remain (modest dataset size, single imaging modality, and simplified classification scheme), this integrated approach enables more reproducible and scalable analysis across large datasets.

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## 294. Fear of the Black Box: Interpretable Machine Learning for Bulgarian Development-Led Archaeological Surveys

*Nadezhda Kecheva (Bulgarian Academy of Sciences)*

### Introduction

Large-scale archaeological surveys generate massive, standardized datasets that are often under-utilized, relegated to simple "gradient maps"—colloquially, "blob maps"—of artefact density. This approach suffers from three critical flaws: it fails to quantify observation biases (visibility, land cover, surveyor methods), struggles to move beyond the "site vs. off-site" dichotomy, and typically mishandles spatial autocorrelation—treating artifact clustering as statistical noise rather than meaningful archaeological signal.

This paper presents a three-component interpretable machine learning framework using more than 26,000 survey polygons from four Bulgarian pipeline corridors. We progressively disentangle archaeological patterns from survey bias through spatially-aware predictive modeling, process-separation analysis, and ground-truth validation against ~100 excavated areas.

### Materials and Methods

Our dataset consists of more than 26,000 georeferenced survey polygons. Predictive features include survey conditions (visibility, land cover, methodology, team, etc.) and landscape variables (elevation, slope, topography, distance to water, etc.).

#### Component 1: Spatially-Aware Landscape Modeling

We will quantify spatial autocorrelation using Moran's I at multiple scales (500m-15km) to characterize artifact clustering. This informs our spatial cross-validation design, ensuring test areas are spatially independent from training areas. We will develop a Random Forest model validated with spatial blocks determined by autocorrelation range, providing honest generalization performance for predicting new corridors. We hypothesize that spatial cross-validation will yield substantially lower accuracy than standard validation, quantifying the spatial leakage effect—where models exploit proximity rather than learning true environmental predictors. Feature importance rankings will reveal whether survey conditions rival landscape factors in structuring artifact distributions.

#### Component 2: Process-Separation Modeling

A two-stage hurdle model will separately analyze: (1) detection (presence/absence of artifacts) and (2) intensity (artifact density when present). Both stages use spatial cross-validation with identical predictors. We hypothesize that detection will be dominated by survey bias (visibility, land cover, team effects, etc.) while intensity will be driven by landscape factors (water, topography, erosion, etc.), testing whether bias and archaeology operate at different stages of data generation.

#### Component 3: Excavation Ground-Truth Validation

One corridor includes ~100 targeted excavations plus construction discoveries, providing four ground-truth categories: (1) survey detected artifacts → structures confirmed (true positives), (2) survey detected artifacts → only plowzone scatter (false positives—redeposition or destroyed sites?), (3)

survey detected artifacts → sterile (false positives—survey error), and (4) survey missed → construction found sites (false negatives—detection failure).

We will assess: What proportion of surface scatters represent real sites versus redeposition? What characterizes missed sites? Do model probabilities correlate with excavation outcomes? This tests whether predictive models identify archaeological significance or merely replicate visibility patterns. Sensitivity Analyses: Spatial scale sensitivity (multiple cross-validation block sizes), feature stability (bootstrap resampling to confirm importance rankings), model comparison across different machine learning algorithms to validate that findings reflect data structure rather than methodological artifacts, and threshold optimization for imbalanced data.

#### Expected Outcomes

Component 1 will establish that artifact clustering reflects meaningful spatial processes at multiple scales (site-internal, local settlement, regional environmental). Spatial cross-validation will reveal substantially lower but honest accuracy compared to standard validation, quantifying how spatial leakage inflates performance metrics. Feature importance will likely show survey conditions rival or exceed landscape factors, demonstrating that detection bias structures observed distributions as much as archaeological reality.

Component 2 will test whether bias and archaeology can be statistically separated. If detection and intensity stages show divergent feature importance, it provides a pathway for bias correction. If not, it reveals that observation bias pervades all survey data levels.

Component 3 will determine whether surface survey predicts archaeological significance or visibility conditions. By distinguishing sites with features "in situ" from artifact scatter through excavation validation, we assess predictive model utility. False negative analysis will quantify detection failure rates and identify contexts where survey reliability is compromised. This ground-truth validation is rare in archaeological predictive modeling.

#### Discussion

This three-component framework transforms survey data from "blob maps" into quantitative, bias-aware, validated landscape models. Spatial autocorrelation is recognized as an archaeological signal, not noise. Process separation tests whether bias operates differently than archaeology. Ground-truth validation empirically tests predictive model meaning.

By using Random Forest as an inferential tool rather than a "black box," we quantify long-debated impacts of visibility and methodology. This approach offers a path toward rigorous, honest, and archaeologically meaningful predictive modeling, transferable wherever standardized surveys and validation excavations exist.

### 328. 3D Models as Research Infrastructures: workflow and architectural palimpsests at the Theatre of Marcellus

*Marika Griffio (Sapienza Università di Roma)*

*Carlo Inglese (Sapienza Università di Roma)*

*Simone Lucchetti (Sapienza Università di Roma)*

This paper presents an ongoing research project on the Theatre of Marcellus and the southern sector of the Campus Martius (Circus Flaminius) as a laboratory for rethinking the role and potential of 3D models in the archaeology of architecture. Rather than offering yet another reconstruction of the monument, the contribution discusses how surveying, modelling, annotation, data management and communication can be organised within an integrated workflow, transforming the 3D model from a "final product" into a genuine infrastructure for research, teaching and public engagement, in line with recent developments in digital heritage documentation (Remondino 2011).

The project emerged at the intersection of two needs: on the one hand, the request by the Soprintendenza Capitolina for a reliable digital model to redesign the lighting system of the theatre; on the other, an academic research

agenda focused on the southern Campus Martius. This convergence enabled an interdisciplinary activity involving architectural historians, archaeologists, conservators and specialists in surveying and digital modelling, and situates the work within a broader “3D archaeology” understood not merely as a visualization technique, but as a cognitive and critical device (Forte 2014).

From a historical-architectural perspective, the Theatre of Marcellus is a paradigmatic case. Initiated by Julius Caesar and inaugurated by Augustus in 13 BC, it stabilises in masonry the Roman theatre type and is embedded in the monumental system that includes the temple of Apollo Sosianus, the Portico of Octavia and the Circus Flaminius, in a sector of the Campus Martius whose topography and settlement dynamics have been extensively studied (Coarelli 1997). Its long history of reuse—from the *mons Fabiorum* and *mons Savelli* to the Savelli-Orsini palace, and then to the excavations and restorations between the nineteenth and twentieth centuries—makes it an architectural palimpsest in which ancient structures, medieval additions and modern interventions coexist and mutually condition one another.

The first phase of the project focused on building a shared metric foundation. For the exterior, a long-range laser scanner was used, capable of acquiring millions of points on the travertine surfaces of the façade; for the internal spaces—vaulted corridors, ambulatories, underground rooms—a compact medium-range instrument was employed. The scans, organised in numerous stations with generous overlap zones, were registered and merged into a single high-density point cloud, which constitutes the reference dataset for all subsequent stages.

From this point cloud, both orthoprojections for plans, sections and elevations and a series of three-dimensional models designed for different purposes were derived. Starting from an appropriately filtered and decimated version of the cloud, a mesh model of the original travertine surfaces was produced, preserving the “roughness” and irregularities of the stone material. For the medieval plastered structures, a continuous NURBS-based model was preferred, capable of effectively rendering the volumetric logic of the built masses. The twentieth-century restoration components, by contrast, were reconstructed in a more idealised manner, based on two-dimensional

sections and moulding profiles, in order to emphasise their nature as deliberately designed and recognisable additions.

This differentiation is not merely technical; it has a critical dimension. Treating the three macro-categories—ancient, medieval and restored fabric—in distinct ways makes the composite nature of the monument legible within the model and allows each portion to be associated with a different degree of adherence to physical reality, geometric abstraction and design intentionality. In the case of travertine, retaining the irregular mesh means foregrounding the time-worn materiality of the surfaces. For the medieval structures, a more regular modelling approach highlights the spatial logic of the building volumes. For the twentieth-century integrations, the reconstruction of profiles enables direct comparison with the canons of the architectural orders and with the documentary sources of the restoration.

A second line of experimentation concerns the use of the model as a basis for lighting simulations. In response to the heritage authority’s request, a dedicated version of the model was optimised for lighting calculation software, with material characterisation (travertine, plaster, tuff) calibrated in terms of roughness, reflectance and colour. The simulations made it possible to test different hypotheses of nocturnal illumination, evaluating their perceptual impact and their coherence with the historical and stratigraphic reading of the monument, and suggested possible strategies for using light itself to reveal the palimpsest-like complexity of the site.

In parallel, the model has been progressively enriched with descriptive and interpretative information, evolving into a prototype 3D repository for the Theatre of Marcellus. Each modelled element can be queried according to a series of attributes: chronology, material, intervention phase, conservation state, supporting documentation. The adoption of consistent metadata structures and controlled vocabularies makes the origin of each piece of information traceable and allows a clear distinction between observed data, hypothesis and interpolation. In this sense, the model moves towards BIM-like or other semantic-modelling logics, yet without sacrificing geometric refinement and surface quality, and while keeping historical and interpretative questions at the core.

From the perspective of historical and archaeological research, this digital infrastructure enables multilevel interrogations of the theatre. It becomes possible, for example, to isolate and compare circulation paths reserved for different social groups in light of the *Lex Iulia theatralis*, to read in section the relationships between vaulted ambulatories and the external elevation, or to follow the superimposition of medieval and Renaissance residential structures onto the Roman *cavea*. At the same time, the model facilitates a dialogue between survey data and written or visual sources, allowing scholars to check the consistency between ancient descriptions, historical views and the present state, and to visualise discrepancies, *lacunae* and reconstructive hypotheses in an immediate way.

On the side of communication and teaching, the project envisages publishing the model—or selected derivative versions—within interactive environments accessible both on site and online. For non-specialist audiences, the possibility of virtually “assembling” and “disassembling” the monument by switching historical phases on and off makes the palimpsest character of the site and the stratified nature of the Roman urban landscape quickly understandable. For students of architecture and archaeology, the model becomes a support for exercises in critical reading, virtual restoration and the design of new visitor devices, and also prompts reflection on the responsibility that graphic and narrative choices bear in constructing the public imagination of the past.

In conclusion, the Theatre of Marcellus proves to be a privileged observatory from which to reflect on the epistemological potential of 3D models applied to complex urban archaeological sites. The experience presented here shows how a model initially conceived for a “practical” purpose—the design of a new lighting system—can, if properly structured, be transformed into an open knowledge infrastructure capable of bringing together metric data, architectural history, archaeology, conservation and communication. The Theatre of Marcellus thus becomes not only an object of study, but also a test platform for defining more reflective practices in the production, management and sharing of 3D data in the field of the archaeology of architecture,

in dialogue with the international debate on digital methodologies for complex built heritage.

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## 331. „Spaces of an Empire“: Revisiting Space Syntax Analysis for Neo-Assyrian Palatial Architecture

*Jannis Werner (University of Cologne)*

### Introduction:

This paper presents the application of Space Syntax analysis to the architecture of Neo-Assyrian palaces. It shows the application of Convex Space Analysis and the caveats the methods have when being used for ancient architecture. The results of this analysis validate the application of Space Syntax for Neo-Assyrian palatial architecture, and while the results do align with the broader understanding of these structures by traditional interpretations, they also present new insights into the structure, potential movement, and function embedded in the spatial layout of Neo-Assyrian palatial architecture.

### Methods and Materials:

Space Syntax as a method has been introduced by Hillier and Hanson in the 1980s and since then found application in several archaeological contexts. In the past, there were different studies and papers on the application of Space Syntax for archaeological contexts. This paper revisited the method and focusses on the application of Convex Space Analysis, a method created for the investigation of spatial layouts of buildings. This was chosen since it is applicable to the archaeological remains and knowledge we could gather about Neo-Assyrian palatial architecture. Which are commonly interpreted based on finds and textual sources, but not based on a reproducible, computational approach such as Space Syntax. For this case study, the two main palaces of the ancient city of Kalhu have been chosen, the Northwest Palace and the so-called Fort Shalmaneser, as the differences in their layout and function enable a solid validation of Convex Space Analysis for Neo-Assyrian palatial architecture. Next to the use of formulas and values offered by Space Syntax, to understand the values, an interpretation based on Fisher (2014) is applied to gain a first understanding of the values.

#### Results:

The resulting values do align with common interpretations and undermine the underlying organisations of the two palaces. Additionally, they also highlight detailed differences in organisation and potential functions of the buildings. Especially, the different characters of the buildings are apparent and highlighted. It can be stated that Convex Space Analysis is applicable for Neo-Assyrian palatial architecture and offers a different perspective to supplement the traditional art historical approach. While also introducing a constant bias method, enabling comparisons.

#### Discussion:

This study demonstrates that Convex Space Analysis within the Space Syntax framework can be effectively applied to Neo-Assyrian palatial architecture. The results complement traditional interpretations by providing a quantitative perspective on spatial organisation and palace function. Revisiting Space Syntax, a method already debated within archaeology, proves worthwhile as

it reveals its potential for analysing ancient architecture when specific requirements are met. Despite these limitations, it offers a reproducible framework that supports comparison and deepens our understanding of Neo-Assyrian spatial design.

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### 335. Towards the Algorithmic Identification of Buildings from Post Hole Locations

*Mathys du Plessis (Nelson Mandela University)*

*Raphaëlle Javet (University of Zurich)*

*Aurèle Pignolet (InSitu Archéologie SA)*

#### Introduction

Post-built architecture often leaves only faint traces in the archaeological record. Once abandoned, wooden structures disappear rapidly, with post holes being the main features that survive in the ground. These subtle remains make the identification and reconstruction of building plans particularly challenging, especially when successive settlements took place in the same location. This problem was at the centre of the dedicated session at the CAA 2025 conference in Athens, “Looking for Wooden Architecture in Post Holes Constellations: Computational Approaches, Methods, and Tools to Reveal the Invisible.” The present paper aligns with this research theme by proposing a new computational approach to help archaeologists detect coherent networks of post holes within complex archaeological features and support the reconstruction of building layouts.

#### Methods

This paper presents an algorithm aimed at the automatic identification of buildings from post hole map data. The algorithm interprets each pair of post holes in the scene as a vector (i.e. a distance and a direction). Performing the dot product on these vectors provides an efficient way of calculating the angle between any two vectors, thereby determining the degree to which any two vectors are aligned. Vectors of similar lengths and similar orientations are candidates for being part of a regular wall in a vanished building as long as they share one post hole. The algorithm iteratively identifies sections of walls starting at the shortest and best aligned vectors and gradually expands the search to longer vectors that are less well aligned. These post holes are

connected by edges to form a graph. Fully connected subgraphs are classified as buildings. Each post hole is allowed a maximum of three connecting edges and is removed from the iterative search process once it has three connecting edges. Once all the straight walls are identified, vectors that are at right angles to each other are included in the iterative search process to include corners in rectangular buildings.

The algorithm has several parameters that can be tuned by the researcher to improve analysis for specific post hole maps. The first of these is the range of vector lengths that are considered. This parameter can be set to only identify buildings where support posts are a specified distance apart.

Expert insight into the construction of the vanished buildings can thus be used to guide the search process. The second important parameter is the minimum alignment angle between vectors. A small alignment angle would result in only very regular rectangular buildings being detected. A larger angle threshold results in the algorithm being able to detect irregular or round buildings. It should be noted that using too large values for either of these parameters increase the likelihood of false positives in the detection process.

#### Results

The algorithm was developed and refined using simulated sites created by scaling, rotating and overlapping post-hole templates of several buildings from literature. The algorithm performed very well on the simulated sites, but this section describes the evaluation of the algorithm on an actual real-world site. This preliminary evaluation of the algorithms was performed on a site for which an expert analysis of the post hole buildings had already been performed (Moreau 2015). This case study was selected because it is particularly challenging in that hole depths, hole sizes and topological information of the landscape were not considered, thereby making the analysis more difficult.

A small part of the site map and identified buildings are replicated in Figure 1 with the human expert interpretation on the left and the algorithm’s interpretation on the right. The algorithm was reasonably successful at identifying

buildings labelled A, B, and C in the figure, although the overall building structure does not exactly match the human expert's interpretation. The algorithm did not perform well on the buildings labelled D and E. Here, the algorithm's interpretation does not resemble realistic building walls. However, in both cases, the human interpretation included areas without any post holes, and this interpretation relied on other archaeological evidence, as the post holes in these areas were not preserved.

Figure 1 illustrates an interesting occurrence where the algorithm's analysis seems to differ considerably from that of the human expert. Building F was identified by the human expert (once again using post holes that had not been preserved), but was not detected by the algorithm. However, the algorithm identified building G, which was not found by the human expert. In this case there seems to be reasonable evidence that human's interpretation is indeed correct (note the triangular shape on the righthand side of building F which matches buildings A, B and D). However, this occurrence does demonstrate that the algorithm may be useful in suggesting alternative buildings and new perspectives that may not have been evident to human experts or that may otherwise go unnoticed.

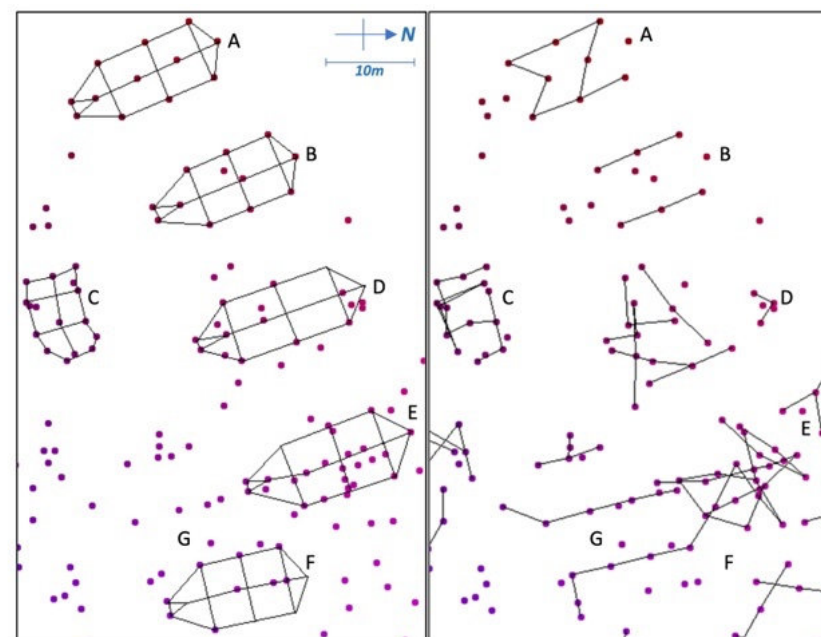


Figure 1: Human interpretation (left) versus algorithm interpretation (right), adapted from Moreau (2015).

## Discussion

The preliminary investigation found that the algorithm was particularly ineffective in extremely dense post hole fields not shown in Figure 1. It is envisioned that including additional information in the analysis, such as stratigraphic context (where available), details regarding post hole fill, hole depth or post hole girth, could enable the algorithm to better separate successive overlapping buildings that once existed on the same location. Although it cannot replace archaeological interpretation, the integration of such an algorithm into archaeological analysis has the potential to significantly deepen our understanding of settlement sites characterised by wooden architecture. More collaboration and input from the broader archaeology community is needed to determine how the algorithm can be refined and incorporated into existing GIS-based tools and approaches.

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### 336. Modular Research Pipeline: Conceptual Work Towards Describing Intentful Research Workflows

*Andrea Göhring (Leibniz Laboratory for Radiometric Dating and Isotope Research, Kiel University)*

*Steffen Strohm (Kiel University)*

*Daniyal Kazempour (Kiel University)*

*Hendrik Raese (Kiel University)*

In recent years, the FAIR and FAIR4RS (see Barker et al. 2022) principles have become central to the scientific ecosystem, providing guidelines for transparency, accessibility, and reusability of research data and software. However, while their normative status is undisputed, their implementation and enforcement remain heterogeneous and uneven. Funders and publishers increasingly demand FAIR compliance (via Data Management Plans or journal policies) yet these mechanisms rarely ensure consistent methodological transparency or reproducibility. Assuming that FAIR and FAIR4RS standards are broadly accepted as guiding frameworks, a critical gap persists: the difficulty of reconstructing how and why specific methods were applied in particular analytical contexts. Intentional design choices, often implicit in code comments, hidden in narrative fragments of a paper, or omitted due to constraints of time and space, remain under-documented, obstructing interpretability, interoperability, reproducibility, and meaningful reuse. If the core

purpose of scientific discourse is the collaborative refinement of valid, plausible, and reproducible results, researchers require structured, resource-sensitive access (low cost, low barriers, realistic skillset expectations) not only to data, code, and outcomes, but also to the procedural logic and epistemic intentions underpinning them.

To address this need, this work advances the conceptual and practical framework of the Modular Research Pipeline (MRP), initially introduced as a synthesis of the Research Data Lifecycle and the Knowledge Discovery in Databases (KDD) pipeline (see Strohm et al. 2025). MRP is conceived as both a descriptive model and an operational scaffold for representing research processes as modular, iterative systems of procedures and products. It merges the lifecycle perspective - concerned with planning, preservation, and reuse - with the computational orientation of KDD, which structures data-driven analysis through selection, preprocessing, transformation, analytical processing and interpretation. By unifying these well-established perspectives, MRP offers an integrative perspective suited for intra- and interdisciplinary research environments, enabling transparent alignment between methodological design and data stewardship.

This contribution aims to provide a graphical and conceptual deep dive into MRP procedures. A graphical representation is chosen to intuitively depict objects, states, and their interrelations, capturing both semantic and functional dependencies: similarities among methods and data types, sequential analytical logic, and temporal or hierarchical relations. The resulting representation forms a dense, human-readable and machine-translatable description of procedures, products, and intentions. From a human-centric perspective, this supports early-stage knowledge transfer between collaborators, later interpretability by reviewers or re-users, and the cross-disciplinary identification of characteristic research designs. It facilitates classification of procedural elements (distinguishing between, e.g., data-driven automation, expert parameterisation, and interpretive reasoning) and enhances explainability by exposing potential methodological black boxes. From a machine-

centric perspective, MRP promotes modular, automatable workflows: explicit step specifications with defined input/output structures, reproducible formats, and linear execution constraints. Standardised pipeline and step descriptions thus emerge as a foundation for transparent, automatable, and comparable research workflows (see also Thierry et al. 2023).

At its core, an MRP step is defined through explicit specifications of expected input, applied method (with parameters and algorithms), and resulting output, complemented by contextual descriptions of intent and local workflow embedding. These steps, combined into full pipelines, operationalise research as modular entities that can be reused, recombined, or iteratively refined. The granularity of such steps determines the balance between comprehensiveness and practicality: overly fine-grained descriptions risk excessive documentation effort, while coarse-grained ones hinder transparency and reusability.

Building on this conceptual foundation, the present work investigates three key research questions:

- (1) To what extent can modularized, generalizable MRP steps (from specific scripts to larger frameworks) be effectively reused across analyses, projects, and disciplines?
- (2) What level of granularity is optimal to balance the investment of time and resources with the benefits of improved knowledge transfer and shared understanding in practical research settings?
- (3) Can the MRP framework, when applied in real-world use cases, serve as a bridge between technical, methodological, and epistemic dimensions of intra- and interdisciplinary collaboration?

These questions are addressed through two exemplary use cases: the pre-processing and analytical treatment of geophysical prospection data, and an ancient DNA (paleogenomic) analysis. Both domains exemplify the challenges of integrating heterogeneous data sources, managing complex

analytical pipelines, and documenting expert-driven methodological decisions. By applying MRP in these contexts, we start to test its capacity for standardisation, interoperability, and cross-domain transferability.

In conclusion, this work elaborates the Modular Research Pipeline as both a conceptual framework and an applied methodology for structuring and communicating research processes in line with the FAIR and FAIR4RS principles. MRP enables the explicit linkage between data, methods, and interpretive reasoning, thereby strengthening the transparency and sustainability of data-driven research. By formalising procedural logic and making methodological intent an integral part of the research record, MRP contributes to bridging the gap between human interpretability and computational reproducibility. It simplifies compliance with evolving FAIR requirements through structured sharing of data, code, metadata, and procedural rationale, and offers a scalable path toward the automation and reuse of well-defined analytical modules. Ultimately, the MRP framework aspires to foster a research culture where methodological clarity, interoperability, and reflexivity become as fundamental as the availability of data and code—advancing both the epistemic robustness and the practical efficiency of interdisciplinary scientific inquiry.

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### 351. Archaeological AI in Data-Scarce Underwater Contexts: Exploring Archaeological Understanding and Machine Learning.

*Benjamin King (NTNU Trondheim)*

*Øyvind Ødegård (NTNU Trondheim)*

*Aurora Hoel (NTNU Trondheim)*

A persistent challenge for applying artificial intelligence in archaeology is the limited availability of large, well-structured datasets suitable for training machine-learning models. Even the most comprehensive archaeological datasets, such as recent aerial or LiDAR compilations with several thousand annotated sites, remain small compared with the scales required for robust and reliable implementation of recent breakthroughs in deep learning and other methods (Argyrou and Agapiou 2022). In the underwater domain, this scarcity is even more pronounced as the acquisition of large datasets is severely constrained by visibility, depth, environmental variability, and prohibitive costs. These factors limit our ability to leverage recent breakthroughs in deep learning for image analysis. Yet autonomous and semi-autonomous robotic systems are increasingly deployed for exploration, documentation, and monitoring of underwater cultural heritage in deep or remote areas. Operating under constraints such as limited communication bandwidth or no human-in-the-loop capability, these systems must continuously decide where to move, what to observe, and how to acquire data that are both technically sound and archaeologically meaningful. They require an integrated archaeological intelligence that guides sensing behavior toward high-quality, contextually relevant data acquisition to perform satisfactorily.

This paper investigates whether geometric models of representing information can complement and enhance autonomous decision-making in data-scarce underwater environments. Specifically, we investigate Peter Gärdenfors's conceptual spaces as a theoretical lens for bridging underwater sensor-technological perception and archaeological understanding (Gärdenfors 2004). Gärdenfors's theory of conceptual spaces is about organizing information as geometric relationships in multidimensional feature spaces. Gärdenfors (2004) describes how to organize information geometrically based on similarity between different quality dimensions that objects possess for categorization. Examples of quality dimensions that can be sorted into different domains include color, weight, space, time, and others. These domains can be plotted as data points in a multidimensional vector space, allowing for measuring similarity based on the distance between clusters of points that create topological boundaries between concepts. In doing so, we can represent information that more closely reflects archaeological domain knowledge.

Our central question is whether a similar representational framework, grounded in archaeologically meaningful dimensions and implemented through multidimensional geometric representation of information, could help autonomous systems reason about underwater features without requiring large training datasets. We suggest conceptual spaces as a complementary framework for how robots could organize observation prioritization and incorporate archaeological domain knowledge into autonomous decisions. Could dimensions derived from sonar and optical sensors, such as reflectivity, geometric coherence, and material consistency, be organized into a conceptual space anchored to archaeological distinctions? And could these archaeological distinctions be defined in historical, contextual, or relational terms rather than purely geometrical ones? Furthermore, could such a framework support situational awareness for tasks like distinguishing cultural from natural features, identifying areas that merit detailed documentation, or planning efficient survey strategies?

The paper will engage with these questions through a theoretical lens by applying a phenomenological approach to explore and discuss the relationship between sensor perception and archaeological perception. This approach seeks to reconcile the embodied and the contextual to archaeological understanding and perception (Rosenberger and Verbeek 2015) with formal, geometric models of machine perception. In addition, machine learning algorithms are rooted in long-standing philosophical positions, making them partial models of intelligence. This allows for discussions surrounding the theoretical foundations of ML in archaeology in combination with phenomenological approaches.

However, we do not claim to resolve this tension, but rather use it as a starting point for a discussion: what might be lost or gained in attempting to express archaeological reasoning within such a formal framework? What is the relationship between ML algorithms and archaeological reasoning? How might the exercise of translation itself clarify both the limits of geometric approaches and the implicit structures within archaeological interpretation?

This paper will use examples drawn from AUV and ROV surveys of shipwrecks conducted by NTNU's Applied Underwater Robotics Laboratory to serve as exploratory probes. We use these examples to ask questions: How do perceptual dimensions present in sensor data correspond to the archaeological distinctions that matter? How might embodied aspects of expert perception—contextual awareness, material understanding—be partially captured or usefully constrained within a geometric model of representation? What methodological framework might remain interpretable to archaeologists while supporting autonomous sensing decisions?

Rather than proposing a finished system, this paper aims to open an interdisciplinary discussion on how archaeological knowledge, phenomenology, and machine perception might inform one another. We outline a theoretical framework for thinking about autonomous systems, not as replacements for human expertise, but as machines that must reason—tentatively and

heuristically—within structures informed by archaeological perceptual understanding. By exploring real challenges in current approaches to underwater documentation, we hope to clarify both the potential and the obstacles, through our theoretical approach, to enhance robotic autonomy in heritage contexts.

## 354. Beyond Borrowed Tools: Towards a Theoretical and Methodological Framework for Digital Archaeology

*Anja Wutte (University of Cologne, TU Wien)*

*Maria Sotomayor Chicote (University of Cologne)*

Digital archaeology has evolved into a central area of archaeological research, transforming how we collect, analyse, and interpret data. Yet, while technological applications in archaeology have grown exponentially, theoretical and methodological reflection on the use of these tools has not advanced at the same pace. Digital archaeology remains mainly characterised by the adoption of methods from other fields such as computer science, geography, architecture, and other disciplines, rather than by the development of theoretically grounded methodologies from within archaeology itself. This imbalance has led to a discipline that excels in technical application, but still lacks a coherent theoretical discourse about its own digital practices. From this starting point, we propose that instead of waiting for methods to be improved by other research fields to reuse them as archaeological research and analysis tools, we invest more in digital archaeological method research. This implies to not just assimilate foreign methods but to actively adapt, restructure and improve methods for archaeological purposes. In turn, this means to invest effort and resources in purposive methodological research.

Based on this core statement, this paper argues that digital archaeology should not be understood merely as the use of digital tools but as a domain of methodological and theoretical research in its own right. Here, the



relationship between theory and methodology lies at the core of this argument and, although it is proper to argue that these two aspects are connected, it is reasonable to fully understand the background, tasks and nuances of both subjects. While theory defines the typology of the questions that archaeologists ask and the interpretative frameworks within which evidence is understood, methodology determines how such questions are implemented in practice. Therefore, the statement “theory guides methodology” encapsulates the reciprocal nature of archaeological inquiry: theoretical assumptions shape methodological choices, and methodological experimentation, in turn, challenges and refines theory. However, both dimensions are often treated separately. Thus, it is essentially a reflexive integration of the two, allowing archaeologists to understand not only the technical affordances of digital methods but also their epistemic implications.

A review of the intellectual traditions in archaeology, from processual, post-processual and Marxist to behavioural archaeology, informs us how these theoretical strands remain relevant in the digital age. However, the recent introduction of computational approaches- from machine learning and 3D reconstruction to network and spatial modelling- requires renewed theoretical engagement. Each of these methods carries implicit models of human behaviour and materiality that must be critically understood if digital archaeology is to be theoretically coherent rather than simply technically competent.

Therefore, we propose that methodological research in digital archaeology should develop along two complementary trajectories. The first involves creating and testing new digital methods within specific case studies, ensuring that innovation remains grounded in empirical archaeological material. The second begins at a more abstract level, designing methodological frameworks and tools theoretically tailored to archaeological questions, which can then be applied to appropriate datasets. Together, these approaches constitute a reflexive cycle of development in which theoretical insight informs methodological design, and methodological experimentation, in turn, contributes to theoretical refinement.

At the same time, the inherent interdisciplinary character of digital archaeology presents both opportunities and challenges. While it draws heavily on external technical expertise, the flow of knowledge should not be one-directional. Archaeologists can contribute to other disciplines by offering perspectives on temporality, uncertainty, and contextual interpretation among others, that challenge reductionist tendencies in other fields. By doing so, digital archaeology can serve as a study case for exploring how computational systems handle complex, incomplete, and significant data at a broader level.

The development of a theoretically informed methodological agenda would be essential to reposition digital archaeology from a consumer of external technologies to an active producer of epistemic and technical innovation.

Such an agenda involves:

- Recognising that all digital methods embed theoretical assumptions;
- Treating methodological design and reflection as legitimate archaeological research;
- Developing evaluation criteria that include not only efficiency and precision but also interpretative transparency and epistemological coherence; and
- Encouraging reflexivity about how digital mediation transforms archaeological reasoning itself.

Ultimately, this paper calls for digital archaeology to become both “archaeology about the past” and “archaeology about archaeology”. Methodological and theoretical research must advance together if digital archaeology is to fulfil its potential as a critical, self-aware, and conceptually independent field. By integrating theoretical discourse with methodological innovation, archaeologists can move beyond borrowed tools to create digital practices that are genuinely archaeological -assimilated in the discipline’s intellectual

traditions, responsive to its interpretative challenges, and capable of contributing meaningfully to the wider scientific and technological landscape.

### 390. DIGital: A Substantive Virtual Field School Experience

*Devin San Nicolas (Northern Arizona University)*

*Tate Whittaker (Northern Arizona University)*

*Ryan Wood (Northern Arizona University)*

*Jarom Craghead (Northern Arizona University)*

*Scott LaRocca (Northern Arizona University)*

*Kayeleigh Sharp (Northern Arizona University)*

Aspiring archaeologists are often unable to pursue practical training due to the high cost of, and limited access to, traditional field schools (Shackelford et al. 2020). Furthermore, the physically and emotionally demanding nature of fieldwork limits participation of differentially abled students who wish to learn more about archaeology or the range of careers for which they may be best suited before entering real-world settings (Kyrilitsias et al. 2020). Such factors serve to diminish inclusivity within the archaeological subdisciplines, limiting access for prospective learners across different sorts of boundaries more broadly. To combat such limitations, immersive archaeology experiences have demonstrated potential to serve as alternatives to traditional excavation and field school experiences (some notable examples include: <http://vrchaeology.com>, Wessex Archaeology!, York Archaeology, DIG Digital, or the CHI 2021 Student Game Competition submission RelicVR). With the latest advancements in AI and Machine Learning, we move one step closer to recreating a real-world experience that is even more robust than virtual reality predecessors (Bickler 2021).

Using a custom-trained AI model, the DIGital team has created a lightweight, web-based virtual experience that allows anyone to learn and practice key archaeological processes, including the pedestrian survey, unit marking,

excavation, artifact recording and analysis, and unit backfilling while consulting with AI field directors who are experts at the site. By incorporating multi-dimensional data recorded over several field seasons, learners are able to carry out pedestrian surveys, select excavation units, record spatial and environmental data, recover and analyze 3D replicas of artifacts, and simulate field and lab work carried out during the regular field season.

With embedded knowledge checks, the DIGital experience assesses comprehension not only of archaeological field work activities but also analysis (Kyrilitsias et al. 2020). Our restricted AI assistant is available for students to interact with, should they have questions or wish to learn more about the site and civilizations being studied. By hosting the experience on a website with a simple and intuitive user interface for efficient first or third-person navigation, virtual field school participants can interact both in and out of VR headsets.

In the process of analyzing the key technological challenges, identifying the range of possible alternatives, and selecting those alternatives that offer the most promising solutions, the team identified key areas in which to make improvements. In this presentation, we will identify the major technological challenges encountered during development and discuss how they were overcome.

When deployed, anyone from anywhere is able to participate in our field school experience, increasing equity and inclusivity in archaeological field experience. Using the open-source Unity format and a custom-trained AI assistant, we overcome not only the financial and geographical barriers of traditional field schools, but also assessment and training problems as well (see also Shackelford et al. 2020; Kyrilitsias et al. 2020).

The approach we present here offers a flexible teaching tool that educators with 3D assets can contribute to and utilize in their in-person or online courses. With the problem properly defined and the solutions outlined, our team – DIGital – offers an equitable and immersive solution that serves anyone with access to the internet.

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### 369. Towards a Framework for Modelling Uncertainty in Archaeological Excavation Information

*Natalie De Schuytener (University of Antwerp)*

Archaeological knowledge production is inherently shaped by uncertainty. Fragmentary material evidence and interpretive ambiguity require archaeologists to infer spatial and temporal relationships from incomplete information. However, data modelling practices often privilege categorical stability and apparent certainty, leading to what has been described as a “new empiricism” rooted in scientific optimism and positivist expectations (Sørensen 2016). This tendency risks obscuring the interpretive complexity inherent to archaeological reasoning. In response, this paper proposes a theoretical framework for understanding uncertainty as constitutive to spatial and temporal interpretation in archaeology, distinguishing between different sources and expressions of uncertainty, and highlighting how they shape interpretive reasoning as well as modelling approaches within archaeological practice.

This conceptual framework, developed through ongoing doctoral research, examines how vague and ambiguous phenomena are encountered, articulated, and formalised in archaeological interpretations. In archaeology, vagueness and ambiguity as uncertain conditions have both epistemic and ontological dimensions (Chapman and Wylie 2016): they arise partly from limits in what can be observed or documented, and partly from the nature of archaeological remains themselves, which are often gradual, overlapping, and resistant to discrete boundaries. Recognising this dual character of uncertainty is essential, since it shapes the reasoning strategies archaeologists use when working with incomplete evidence. These strategies include abductive reasoning, inference-to-the-best-explanation, robustness reasoning, and inference-from-absence, each of which plays a role in evaluating alternative, potentially conflicting interpretations. This framework emphasises how archaeological interpretations develop through cycles of tentative inference, comparison, adjustment, and re-evaluation as excavation progresses and contextual information accumulates. By examining how archaeologists identify vagueness and ambiguity, and keep multiple hypotheses in active consideration through different modes of reasoning, this framework highlights interpretive processes that are rarely visible in structured recording systems. It shows that uncertainty is not simply a temporary lack of information, but a constitutive part of archaeological knowledge, shaping the emergence of spatial and temporal relationships long before they appear in formal datasets or models.

Further, this paper highlights the relationship between interpretive uncertainty and computational modelling in archaeology. Archaeological modelling approaches such as probabilistic frameworks, Bayesian methods, or fuzzy logic increasingly seek to formalise degrees of uncertainty. However, these approaches tend to engage with uncertainty once it has already been formalised, often without fully accounting for the interpretive conditions in which uncertain spatial and temporal relations initially take shape (Hacıgüzeller, Taylor, and Perry 2021). Rather than treating uncertainty as a computational problem to be addressed post-hoc, the framework highlights the interpretive processes that precede formal representation and offers a

basis for modelling approaches capable of acknowledging provisional, parallel hypotheses, and contingent interpretive judgement. In doing so, it contributes to ongoing efforts in computational archaeology to align modelling practices with archaeological epistemology, insisting that robust modelling of archaeological interaction already begins at the reasoning processes through which interpretive claims are first formed. Excavation documentation from Kaymakçı (Turkey) illustrates how uncertainty during initial interpretation is selectively translated as it moves from archaeological notebooks into more formal recording systems. Only by explicitly acknowledging the interpretive work that precedes structured data can digital infrastructures avoid prematurely constraining interpretive possibilities or translating ambiguity into a misleading sense of certainty.

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## 406. Quantifying material costs in Building Archaeology: an AI application of the Taglab tool to Massenzio's circus.

*Domenica Dininno (CNR)*

*Marco Callieri (CNR)*

#### Introduction

How much did it cost to build a circus? Spectacular circuses, which can seat over 250,000 spectators, rank among the most significant sporting venues in history. Their immense size can symbolize large data sets, serving as valuable indicators of economic trends. These venues reflect the financial performance of their regions, showcasing the willingness of local elites to invest in their cities through generous contributions.

Economic history research has, for a long time, primarily relied on literary sources and analyses focused on the production of specific materials. In recent decades, scholarly publications have increasingly concentrated on examining the costs and labor processes involved in various construction projects within the field of architectural energetics. This paper proposes digital methods for studying building archaeology, employing multidisciplinary approaches that integrate socio-economic analyses, architectural energetics [3], advanced digital tools, and AI, including deep learning, in archaeological research investigations. By leveraging AI, we will have faster analysis, saving time and resources. The methodology will be applied to the Circus of Maxentius in Rome. The remains of the cavea, part of the well-preserved carceres, and traces of the spina make it the best-preserved Roman circus and a perfect case study for calculating construction costs.

#### Background

Research on the history of ancient buildings increasingly emphasizes the economic aspects of construction and labor. Scholars aim to quantify materials and labor time to evaluate their significance. Abrams pioneered architectural energetics in the 1980s, applying it to Mayan monuments. In 1997, Janet

DeLaine [1] examined the economics of large-scale projects in imperial Rome through her study of the Baths of Caracalla. Later, Arco analyzed Aztec architecture, and Pakkanen estimated the costs for Greek ship sheds. In 2018, the International Congress of Classical Archaeology addressed the economic aspects of ancient architecture, leading to the publication of "Quantifying Ancient Building Economy," which consolidates diverse research methods and quantification approaches.

Creating 3D data of historical monuments is revolutionizing how researchers analyze these structures. Recent progress in automated segmentation and classification of point clouds and meshes has been remarkable. Many studies focus on segmentation, effectively addressing the needs of various fields like building modeling, documentation, and cultural heritage preservation. Sit-hole introduces an automatic segmentation technique for detecting bricks in masonry walls using point clouds, assuming the mortar channels are sufficiently deep and wide. Osés et al. utilize machine learning classifiers, such as support vector machines and decision trees, to classify masonry walls. Others have developed algorithms for segmenting masonry blocks in point clouds using a 2.5D approach, which generates images from the LiDAR system's intensity attribute. Some studies utilize supervised methods, which are crucial for an effective training phase that informs subsequent classification solutions based on machine learning.

This article proposes the use of Taglab (<https://taglab.isti.cnr.it/>), an open-source semantic segmentation software that utilizes AI and deep learning to annotate and characterize ortho-images. This tool, initially developed for marine biology, has already been successfully applied to built heritage to identify stratigraphic units [3]. This study demonstrates Taglab's ability to distinguish individual building components over large portions of the structure in a short time, with potential implications for archaeological architectural energetics.

## Methods and materials

This paper endeavors to quantify construction components through an integrated, digital, and interdisciplinary framework. The aim is to develop a

strong methodology that integrates Taglab and AI with virtual modeling to enhance the financial evaluation process and support ongoing academic research.

The methods employed to quantify the construction costs of the circus are: a) decomposing buildings into measurable components and quantifying them, b) counting the number of bricks in a section of the circus using modern, AI-based classification tools, and c) estimating the volumes and materials in ancient buildings through architectural energetics in archaeology.

We propose a more streamlined classification method that aims to reduce manual effort. In our case study, the quantification of architectural elements will be conducted using orthophotos generated through photogrammetry and the TagLab tool to exploit AI-based segmentation (both assisted and automated). The images were imported into the software, and a specialized dictionary was developed for annotating various regions and individual building elements, such as bricks, sesquipedali, and tufelli, among others. The segmentation process utilized various assisted annotation tools implemented in TagLab, making it easy to annotate large portions of the masonry in detail. Quantitative and metric data, such as the quantity and size of regions, their shape, and geometrical characteristics, were extracted to support a comprehensive statistical analysis. The annotated images were then used to train a fully automatic classifier and to test a fully automatic annotation workflow. The advent of these tools facilitates the coverage of extensive areas, enabling the collection of more comprehensive data for statistical evaluations, in contrast with the traditional method of sampling small areas and extrapolating findings.



### Preliminary results

The results of the classification are promising, as illustrated in the accompanying figure. This enables a deeper understanding of the masonry, facilitating logical conclusions about construction methodologies. The data obtained from this analysis can be dissected to assess various architectural energies, effectively breaking down buildings into quantifiable components. By extracting statistics pertinent to quantity and size, we can establish a solid foundation of numerical information. Furthermore, the tool employed facilitates this analytical process, aiming towards automated data processing. The forthcoming phase involves generating the classifier and training the neural network to enhance predictive accuracy and efficiency. We attained strong results regarding accuracy. The categories of opus and tufelli were readily identified, despite some instances of damage. This outcome underscores the level of detail that can be achieved.

Fine-grain segmentation proves beneficial in restoration contexts by facilitating the detection of small cracks or damaged regions. Defining classes accurately is crucial for the effective functioning of the tool, especially when compared to manual segmentation processes. Accurate class definitions enhance performance and reliability, leading to more precise outcomes in data analysis.

### Discussion

The proposed segmentation methodology offers several advantages, including faster classification times relative to manual techniques, and straightforward data input that relies solely on orthophotos—images widely utilized in archaeology and restoration. Additionally, the training set can be reutilized for analyzing buildings from the same historical era or constructed with similar materials, taking into account the roles of various workers. A deep learning-based approach will be valuable for accelerating classification activities in large and complex scenarios, provided that the training data sets are diverse enough. Overall, the calculation of the various typologies (including bricks, sesquipedali, marble, tufelli, etc.) will be more efficient, allowing for easier examination and enhanced timing in the study of architectural energetics.

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## 436. From 3D Models to VR: Multi-Scalar Viewing for Neolithic Art

*Dana Alnafour (Tsukuba University)*

Archaeology has always worked with media. As media change, the ways we present and understand archaeological content also change. Earlier broadcast and television formats shaped public access and interpretation; more



recent interactive and on-demand media allow audiences to engage with archaeological content in participatory ways (Clack and Brittain 2007, 13–17). The layered nature of media culture is important here. Media archaeology treats media history as overlapping strata rather than a linear sequence, a layered and multitemporal construction in which media and information can transfer, resurface, and find new uses, contexts, and adaptations; this methodology—reading history as a fold of time and materiality and at times “re-wiring temporality”—clarifies how contemporary digital formats act as an epistemological switch that conditions what we can see, compare, and discuss about the past (Parikka 2012). In virtual reality (VR), aesthetic experience builds on long traditions of spatial depiction, extending them through binocularity, tracking, and interactivity to produce naturalistic depth and situated viewing (Tavinor 2022).

This paper applies that media-aware perspective to Neolithic material, combining different documentation levels and source media—archival and excavation reports, stratigraphic plans, and digitized, documented artefacts—within a VR workflow. It reports three cases that organize spatial relation in different ways to support understanding and appreciation of artefacts and architecture: (1) visualization of archaeological context at Cafer Höyük, (2) a virtual reconstruction of an immersive domestic space at Cafer Höyük, and (3) a virtual experience of a photogrammetric model of Structure AB at Karahan Tepe. The aim is to show how visual documentation, 3D modelling, and VR present three-dimensional entities within a scalar space that links the human avatar, the artefact, and the built environment—improving contextual understanding, supporting multi-scalar exploration, and strengthening artistic appreciation at human scale.

Photogrammetry-based 3D modelling was produced in Agisoft Metashape for two data types: selected artefacts from Cafer Höyük with artistic features, and the monumental architectural structure Structure AB at Karahan Tepe. Reconstructed excavation areas and a house were prepared in Blender using excavation reports, stratigraphic documentation, and comparative evidence for the domestic reconstruction. The immersive environments were hosted

on Spatial.io as the VR platform. For closer inspection of object surfaces, Sketchfab links were embedded within Spatial.io so users can open and interact with the same 3D models directly; where available, associated microscopic observations are linked to the models.

Across the three VR levels, the experience becomes spatial, relational, and readable at human scale. Visualizing the archaeological context at Cafer Höyük reconnects artefacts with the documented excavation reality by situating them within reconstructed general areas of phase-appropriate settings. Users read phase, architecture, and object together, and scale is judged by standing and seated viewpoints rather than by detached images. The domestic reconstruction offers an evidence-informed, lived interior that makes circulation, materials, and plausible placement perceptible, while a clear path back to the documented area keeps reconstruction and evidence distinct. The direct photogrammetric experience of Structure AB at Karahan Tepe turns plan-view knowledge into embodied perception, where enclosure, pillar rhythm, the upward axis, and sculptural features are encountered through movement and viewpoint.

This arrangement supports multi-scalar exploration and contextual understanding: movement from site or area to room and then to object or surface clarifies where details become legible and why placement matters. Emotional engagement follows setting—reflective in the stratigraphic visualizations, intimate in the domestic scene, and focused and awe-like in the monumental space—without forcing narrative claims. Cognitive response benefits from user interactivity: orientation, poise, and surface treatment are easier to appraise when the viewer changes height, angle, and distance, and embedded 3D links enable close reading of textures and modelling decisions. In combination, these conditions support artistic appreciation through the relation of a human viewer, a three-dimensional object, and a built environment. Interpretive depth grows from seeing material, form, and space together, while the workflow keeps archaeological documentation and reconstructed imagery explicitly separated and comparable.

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## 438. Archaeology Information Modeling - Conceptualization and Pilot Study of BIM-Based 4D Excavation Database Systems

*Bjarne Kortmann (BerGSAS)*

Excavation documentation is a constantly evolving field, experiencing more rapid and diverse developments than excavation methodology itself. The critical importance of proper documentation and reliable research data management in our discipline is increasingly recognized, with the FAIR principles for research data—Findable, Accessible, Interoperable, and Reusable—now familiar to nearly all archaeologists. While there is broad consensus on these principles and great similarity in the data categories produced (such as texts, coordinates, 2D representations, etc.), significant heterogeneity exists in the database systems used across excavation projects. Moreover, few databases can integrate all excavation data categories, resulting, for example, in the isolation and underutilization of 3D data despite its high potential.

In the construction industry, the commercial benefits of interoperability and reusability, as well as the holistic integration of all project data and the

resulting reduction in user error, led to the development and widespread adoption of the concept of Building Information Modeling (BIM). BIM aims to fundamentally improve data management, which, in construction just as in archaeology, has traditionally been characterized by isolated 2D drawings, separate data forms, and countless individual files. By integrating all project data with three-dimensional representations of the features they relate to, into a single digital model, BIM creates a 3D model that functions not only as a visualization but also as an object-oriented database.

As with CAD and GIS, the most widespread BIM software are commercial products employing their own data structures and proprietary data formats. To make BIM data interoperable, an open data standard was developed by a large consortium that simultaneously provides an ontology of objects, relationships, and other data definitions, as well as a flexible, future-proof file format. This standard is referred to as Industry Foundation Classes (IFC). In recent years, the first software capable of natively creating BIM data in that format—rather than just converting to it on export—has been developed, strictly adhering to the data structures mandated by IFC. Although still in an early testing phase, this software, BlenderBIM, provides a promising Free and Open Source Software (FOSS) solution for the creation of IFC BIM data. This approach, employing international open standards and FOSS software, is usually referred to as openBIM, and coincides with many of the principles of FAIR research data management.

While BIM has been applied in cultural heritage management for historic buildings and in archaeology to aid virtual architectural reconstructions, its potential for the comprehensive documentation of excavations has not been previously explored. The vast majority of previous applications in archaeology utilized commercial BIM solutions ('closedBIM') and all remained within its original domain, architecture. This talk addresses the potential advantages of using an openBIM-based data management approach for excavation data compared to traditional methods (such as GIS and SQL databases) and examines the extent to which existing BIM data standards and software can be utilized for this purpose. The presentation draws on research conducted as part of a master's thesis, which led to the

conceptualization of a methodology based on open data standards, ontologies, and open-source software, and the creation of a functioning, holistic 4D database system. This preliminary concept, termed Archaeology Information Modeling (AIM), represents a novel approach to excavation data management and was tested on a conceptual, semantic, and technological level in an initial case study using data from an excavation area of a long-term project in Ethiopia.

The results of this study indicate that the adoption of BIM could be highly beneficial to archaeology, with IFC as a promising candidate for structuring excavation data, both as an ontology and a file format, and BlenderBIM as a likewise promising, although unpolished, software solution for this. Archaeology Information Modeling works, and could already be used as a methodology for FAIR excavation documentation, producing a holistic database that can be navigated both in the traditional way of text-based queries and by navigating the 3D space and interacting with the 3D representations. AIM vastly improves upon previously developed approaches for 3D excavation databases, but more time and optimizations are required to make it a truly convincing replacement, rather than an addition, to already established database systems.

## 457. Decoding Archaeological Space: A Space Syntax Study of the Hellenistic Baths at Sicily

*Mei Yang (UAB)*

Sicily is located in the center of the Mediterranean Sea, surrounded by the sea on three sides. Since ancient times, it has been a hub for Mediterranean shipping, a key area contested by the Greek, Phoenician, Carthaginian, and Roman powers, and an important node for the exchange and integration of diverse civilizations. During the Hellenistic period, the cities on the island flourished, and the number of public buildings significantly increased. Among

them, public baths, as important spaces for social life, reflected the unique urban culture and social customs of the time.

This study combines architectural design theory with the Space Syntax method and uses the Depthmap software to analyze the spatial structures of multiple bath site ruins in Sicily. By converting the bath building spaces into data models and adopting spatial syntax indicators such as Integration and Connectivity, the spatial layout was visually presented and quantitatively studied. The aim of the research is to reveal the organizational logic of the internal spaces of the baths and their relationship with social functions, providing a new analytical perspective for understanding the spatial characteristics of public buildings during the Hellenistic period.

Unlike previous studies that mainly focused on the excavation of findings and the interpretation of historical documents, this research attempts to explore the social logic of architectural spaces through quantitative and graphical methods, thereby providing new evidence and theoretical support for understanding the transformation of bathing culture in the Mediterranean region from ancient Greece to ancient Rome.

## 459. A theory-guided machine learning framework for archaeological science

*Vana Orfanou (Ludwig Maximilian University of Munich)*

*Niklas Stausberg (Ludwig Maximilian University of Munich)*

### Introduction

Archaeological science is currently at a crossroads owing to the fast-growing development and application of machine learning (ML) and AI methods. As novel analytical tools become available for the study of past material culture, it is hardly surprising that theoretical and methodological concerns arise. Archaeological science is well-acquainted with such cycles of analytical innovation, followed by a sharp rise in scholarly aspirations, to eventually plateau between new analytical possibilities and managed expectations. Isotope

analyses for the provenancing of metals and ancient DNA analyses are two such examples.

In the last five years, it is ML and AI methods that stir the waters of archaeology (Bellat et al. 2025). Such methods can both complement archaeological interpretations and open novel ways to address (new and old) questions. However, the nature of the archaeological record presents persistent and discipline-specific limitations; archaeological data are both scarce and complex. These inherent constraints directly impact the application of machine learning pipelines borrowed from other disciplines. Here, we discuss a theory-guided ML framework to address these inherent restrictions and use a case study to illustrate how it can augment interpretations of archaeological materials with specific reference to analytical datasets.

Archaeology and machine learning walk into a bar: discipline-specific constraints

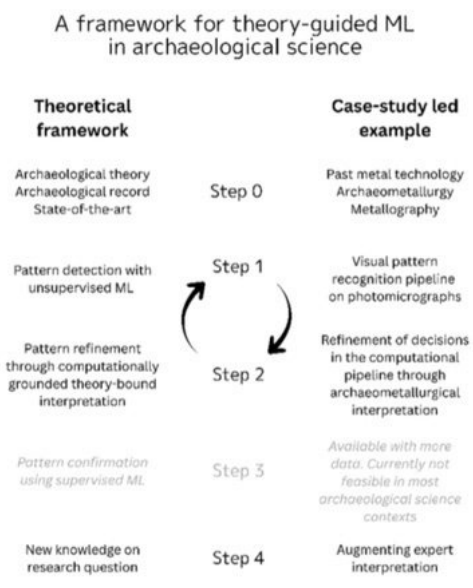
The archaeological record is unlike most data sources with direct implications for ML applications. Its defining feature is the serendipity surrounding the preservation and retrieval of material remains, which are scarce and, in turn, often deemed too valuable for invasive analyses. This limited availability of data does not support the scale that most ML algorithms require. Furthermore, data from archaeological materials shaped by early technologies and altered through long-term physico-chemical deterioration processes are intrinsically heterogeneous and complex. For example, ancient metals exhibit significantly more complex structures than modern metals. As a result, standard ML pipelines cannot be directly transferred to archaeological materials. Even mixed-method frameworks that combine theory-driven interpretation with ML methods (e.g. Computational Grounded Theory developed for social scientific research) struggle in this domain. For any meaningful ML application on the small, complex and heterogeneous analytical archaeological data sets, a move beyond uncritical reliance on unsupervised pattern detection is imperative.

In addition, archaeological datasets are not neutral. They are shaped long before any analysis or the application of ML algorithms starting with the

nature of the archaeological record and followed by sample selection and analytical possibilities. This creates a built-in filtering process in which any available data already reflect layers of expert judgement and contingencies of discovery. Thus, any computational approach must account not only for small and complex datasets, but also with the fact that the data themselves carry the imprint of the prior decisions of the researcher.

Towards a theoretical discourse

Constraints of scarcity, complexity and sampling bias dictate that any ML application needs not only to factor in, but also to build on the researcher’s theoretical grounding. Here, we address this through proposing an adapted framework for integrating ML into archaeological science that anchors algorithmic steps in domain expertise, theoretical reasoning, and established analytical practice (Fig. 1).



We start by acknowledging that existing data and theories already guide how patterns are initially sought before any ML application (Step 0). In addition, theory-bound interpretations are critical for tuning the key parameters (hyperparameters) of unsupervised ML applications and for iteratively refining those choices as patterns emerge (Steps 1 & 2). Even though scarcity of archaeological data presently limits pattern confirmation through supervised ML (Step 3), we argue that theory-guided evaluation of computationally identified patterns can augment initial archaeological interpretations (Step 4). As such, the nature of ML in this workflow is complimentary to traditional theory and scientific expertise and human-led decisions are seen as a strength.

#### Case study

We demonstrate the application of the proposed framework with a case study based on a large corpus of prehistoric metal artefacts from the Carpathian Basin (Orfanou et al. 2024). Archaeometallurgical interpretation of elemental and metallographic data suggests that hoarded metalwork in the southern Pannonian Plain during the Late Bronze Age followed distinct technological pathways that reveal communities of practice across a wide region with shared conventions in resource management, alloying, metalworking, and use. To explore alternative patterns structures and / or nonlinear relationships that fall outside the existing expert-defined interpretation, we embedded an unsupervised image-analysis pipeline adapted with modifications from Cohn and Holm (2021) to photomicrographs of ca. 200 polished metallurgical samples into the proposed theory-guided ML framework. This pipeline is specifically designed for small, unlabelled microstructural datasets and leverages the representational power of deep convolutional networks through transfer learning. Photomicrographs were first standardised (brightness and contrast normalization, resizing and tiling), before extracting high-level feature vectors using the VGG16 architecture pre-trained on ImageNet. Finally, we applied PCA to reduce the dimensionality of the feature vectors and k-means clustering to identify recurrent morphological signatures.

Theoretical considerations can productively guide the researcher's decisions in the application of ML workflows - from preprocessing to final interpretation. We use the archaeometallurgical case study to illustrate how ML algorithms can augment and enrich previous expert interpretations. We stress the limitations of working with a small, regionally bounded corpus and generic pre-trained networks. Importantly, the proposed framework makes the layered biases of the dataset and of the researcher explicit. By leaning into this subjectivity systematically and critically, we use ML to probe our interpretive habits and create a space that is intuitive to scholars of past material culture.

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## S4: Computer Applications in South Asian Archaeology: Digital Innovations in Heritage Research and Preservation

*Kamani Perera, Chartered Institute of Personnel Management*

*E M N Perera, Supreme Court of Sri Lanka*

*Anushka Earskin, Chartered Institute of Personnel Management*

*Indika Wijayasriwardana, Union Bank Colombo PLC*

**Location:** Hörsaal 05

**Session Format:** Standard

The digital preservation of archaeological heritage is gaining unprecedented significance in South Asia, a region marked by historical depth, cultural diversity, and vulnerability to urbanization, climate change, and conflict. This session explores how emerging technologies—3D scanning, GIS-based modeling, virtual reconstructions, and digital repositories—are transforming documentation, conservation, and interpretation practices across India, Sri Lanka, Nepal, Bangladesh, and Pakistan. Beyond technological demonstrations, the session critically examines challenges of accessibility, data sovereignty, and digital ethics, with particular attention to decolonial and community-centered frameworks. Case studies will highlight innovative yet resource-conscious approaches to safeguarding endangered sites and integrating indigenous knowledge systems into digital heritage. By fostering dialogue among archaeologists, technologists, and policy-makers, this session aims to strengthen regional collaboration while contributing to global debates on equitable digital stewardship. It situates South Asia as both a beneficiary and contributor to international discourse, offering transferable insights for sustainable and inclusive digital heritage futures.

### Session Rationale and Objectives

South Asia is home to a vast and diverse range of archaeological heritage, covering from the ancient Indus Valley Civilization and Anuradhapura's monumental ruins to medieval Buddhist monasteries in Bangladesh and Islamic urban forms in Pakistan. However, increasing threats such as urbanization, climate change, looting, neglect, and political conflict have rendered many sites vulnerable. Traditional conservation approaches, while important, are often insufficient in ensuring long-term access and safeguarding the information embedded in these cultural assets.

In response, digital preservation—encompassing digitization, 3D scanning, GIS mapping, virtual reality reconstructions, and digital repositories—has emerged as a vital complementary tool for archaeological conservation in the region. Yet, the practice of digital heritage preservation in South Asia remains fragmented, underfunded, and often disconnected from local communities. Furthermore, issues of digital colonialism, data ethics, intellectual property, and capacity gaps hinder the realization of truly inclusive and sustainable digital preservation practices.

This session is proposed to bring together archaeologists, digital humanists, heritage professionals, technologists, archivists, and policy-makers to:

1. Showcase recent initiatives, technologies, and methodologies in digital preservation of archaeological heritage in South Asia.
2. Explore the socio-political, ethical, and infrastructural challenges of digital preservation in the region.
3. Discuss inclusive and community-centered frameworks for digital archiving and access.
4. Strengthen transnational and interdisciplinary collaborations among stakeholders.
5. Envision pathways for regional digital heritage networks that promote resilience, equity, and cultural continuity.

### Relevance to CAA Beyond Geographical Vicinity



While the session focuses on South Asia, its relevance extends far beyond regional borders. The methodological, ethical, and collaborative dimensions align closely with CAA's mission:

**Methodological Innovation:** South Asia offers low-cost, high-impact applications of computational tools (e.g., photogrammetry with drones, open-source GIS) that can inspire globally transferable models for heritage management under resource constraints.

**Ethical and Epistemic Contributions:** The focus on decolonial, community-based digital practices contributes directly to global debates on knowledge equity, data ownership, and digital colonialism in archaeology.

**Scalability and Data Diversity:** The region's archaeological range—from pre-historic cities to sacred landscapes—provides a unique testbed for adapting computational methods across varied heritage typologies.

**Transnational Collaborations:** By aiming to establish a South Asian digital heritage network, the session advances South–South and South–North co-operation, strengthening the global digital archaeology community.

**Contribution to CAA's Mission:** By bringing underrepresented regions into dialogue, this session promotes inclusivity and global diversity in computational archaeology.

### **Session Themes and Topics**

The session welcomes paper presentations and project demonstrations under (but not limited to) the following themes:

#### **1. Technological Innovations and Practices**

- 3D documentation of archaeological sites (e.g., photogrammetry, LiDAR, drone mapping).
- Virtual and augmented reality applications for public engagement and education.
- GIS-based mapping and predictive modeling of archaeological landscapes.
- Development of open-access digital archives and metadata standards tailored to South Asian contexts.

#### **2. Case Studies from the Region**

- Site-specific digital preservation efforts (e.g., Sigiriya in Sri Lanka, Mohenjo-daro in Pakistan, Lumbini in Nepal, Mahasthangarh in Bangladesh, Hampi in India).
- Integration of local oral traditions and indigenous knowledge systems into digital heritage narratives.
- Digital storytelling and crowdsourced memory initiatives around archaeological heritage.

#### **3. Ethical and Legal Dimensions**

- Ownership, repatriation, and control over digitized archaeological materials.
- Data sovereignty and cross-border access to shared cultural heritage.
- Intellectual property rights, community consent, and safeguarding sensitive cultural knowledge.

#### **4. Capacity Building and Collaboration**

- Building local and regional expertise in digital heritage technologies.
- South–South collaboration and knowledge-sharing mechanisms.
- Role of universities, NGOs, and public institutions in fostering sustainable digital heritage ecosystems.

#### **5. Future Visions**

- Resilience of digital archives in the face of natural disasters and conflict.
- Artificial Intelligence and Machine Learning in archaeological research.
- Blockchain applications for provenance tracking and authenticity.
- Designing immersive digital heritage experiences for younger generations and diaspora communities.

### Format and Structure

The session will be structured as a 90–120-minute panel, allowing for diverse formats:

- 3–5 academic paper presentations (15 minutes each).
- 1 project demo or virtual heritage experience (10–15 minutes).
- Moderated discussion and Q&A (20–30 minutes).

### Target Audience

- Scholars and students in archaeology, digital humanities, heritage studies, South Asian studies.
- Archivists, museum professionals, and librarians.
- Technologists and digital preservation experts.
- Policy-makers and government officials in cultural ministries and departments.
- NGOs and community organizations working in heritage conservation.

### Relevance to South Asia and Global Context

This session is timely and relevant as South Asian countries increasingly recognize the value of digital strategies in preserving their cultural patrimony. With growing digitization efforts (e.g., the National Digital Repository in India, Sri Lanka's Central Cultural Fund projects, UNESCO-supported archives in Nepal and Pakistan), there is an urgent need to build regional dialogue, share best practices, and confront common challenges.

At the same time, global frameworks such as the UNESCO Recommendation on Open Science (2021) and the Charter on Digital Heritage call for inclusive, rights-based approaches to digital heritage. This session contributes to advancing these goals from a South Asian lens, advocating for contextualized, ethical, and equitable digital preservation practices that empower local custodians while promoting global access and recognition.

### Expected Outcomes

- A platform for presenting cutting-edge digital heritage research and practice in South Asia.
- Identification of common gaps, needs, and collaborative opportunities across the region.
- Recommendations for policy frameworks and funding models to support long-term digital preservation.
- Initiation of a regional network or working group focused on digital archaeological heritage in South Asia.
- Possible post-session publication or digital exhibition of featured projects.

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| <b>15:10 – 15:30</b> | <b>*cancelled*</b> 4. Digital Revival of Afghanistan Buddhist Heritage site: Virtual Reconstruction and Preservation<br><i>Ghulam Mortaza Durrani (Sediqi Group I.T Solution Provider)</i> |
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| <b>15:30 – 16:00</b> | Coffee break |
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| <b>16:00 – 16:20</b> | 7. Digitally Preserving the Cultural Legacy of the Kalasha People: A Technological Approach to Saving Endangered Ethnological Artifacts in Chitral, Pakistan<br><i>Aurangzeb Aurangzeb (Hazara University Mansehra KP)</i> |
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| <b>16:20 – 16:40</b> | 29. Preservation of Monuments of Ekamrakshetra<br><i>Ranjit Kumar Das (Indian Institute of Technology Bombay); Rasmita Mohanty (Tolani College of Commerce Mumbai)</i> |
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| <b>16:40 – 17:00</b> | 141. 3D Digital Reconstruction and GIS Mapping of Mahasthangarh: Integrating Archaeological Data for Virtual Preservation |
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*Zillur Rahman (Ahsanullah University of Science and Technology)*

**17:00 – 17:20** 183. A Mobile Application for Sex Estimation from Femur Measurements: A Practical Tool for Bioarchaeological Applications

*Lanka Ranaweera\**; *Eranda Cabral (University of Colombo)*; *D. M. P. V. Dissanayake\**; *W. S. V. Lakshan\**

*\* University of Kelaniya*

**17:20 – 17:30** Break

**17:30 – 17:50** 289. Digital Gandhara Project Preserving Buddhist Heritage in South Asia, Khyber Pakhtunkhwa, Pakistan

*Numan Anwar (director of archaeology and museum of khyber pakhtunkhwa Pakistan)*

**17:50 – 18:10** 334. Mapping Economic Networks Through Metal: A Spatial Database Approach to Roman Coin Hoards in Early Historic Tamilakam

*Rizvan PS (University of Hyderabad)*

**18:10 – 18:30** 342. Geospatial Approaches to Cultural Heritage Documentation: Remote Sensing and GIS Applications in Burhanpur, India

*Manasi Patil (Independent)*

**18:30 – 18:50** 397. Building an R Shiny-based open archaeological database for the Indus Civilisation in north-western India: integrating spatial, chronological, and cultural data

*Ashish Verma (CSIC-IMF Barcelona)*; *Francesc C. Conesa (Social Sciences, Heritage, and Food*

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*(SOCIALPAT), IPNA-CSIC)*; *Rajesh SV (University of Kerala)*; *Abhayan GS (University of Kerala)*; *Juan José García-Granero (CSIC-IMF Barcelona)*

**18:50 – 19:10** 419. Making the Absent Heritage Visible: Using Low-Cost and Portable Digital Tools to Document Heritage at Risk Sites in the Late Mughal Town of Farrukhnagar, India

*Simran Kaur (University of Exeter)*

**19:10 – 19:30** Discussion

## 7. Digitally Preserving the Cultural Legacy of the Kalasha People: A Technological Approach to Saving Endangered Ethnological Artifacts in Chitral, Pakistan

*Aurangzeb Aurangzeb (Hazara University Mansehra KP)*

The museums of Khyber Pakhtunkhwa especially those in Chitral hold rare ethnological collections documenting the cultural practices of the Kalasha people. However, these materials face escalating threats due to incomplete classification systems, limited documentation, unscientific preservation practices, and an increase in illegal trafficking of cultural objects. These challenges are intensified by the gradual erosion of traditional knowledge within the community, as younger generations increasingly shift away from customary lifeways. In response to these intersecting risks, this paper proposes a comprehensive, digitally centered preservation framework aimed at protecting both the tangible and intangible heritage of the Kalasha. The project integrates several advanced digital methodologies. First, 3D laser scanning and multi-view photogrammetry will be used to generate accurate, high-fidelity digital replicas of household items, ritual objects, wood carvings, musical instruments, and other endangered artifacts currently held in regional

museums and private collections. These digital surrogates not only serve as preservation tools but will also support future conservation assessments through metric analysis and condition monitoring. Second, the initiative employs GIS-based cultural landscape mapping, allowing for the spatial documentation of heritage sites, shrine locations, seasonal festival areas, and traditional routes that shape the Kalasha's cultural geography. This geospatial approach helps visualize patterns of cultural change and identifies high-risk zones affected by environmental degradation, tourism pressure, or population displacement. To address gaps in documentation, the project further incorporates a digital cataloguing system built on open-access heritage management platforms aligned with international metadata standards (e.g., Dublin Core, CIDOC-CRM). This database will create a unified, publicly accessible record of Kalasha artifacts—linking 3D models, provenance histories, oral narratives, and conservation status into a single searchable system. Complementing these efforts, community-driven digital storytelling and oral-history recording are embedded as core components. Using mobile recording kits and participatory digital methods, elders and cultural custodians will contribute narratives that contextualize the meanings, ritual functions, and traditional knowledge associated with each object. This ensures that the intangible dimensions of Kalasha heritage songs, myths, ceremonies, craft processes, and memories are digitally preserved alongside the material artifacts. By combining digital documentation technologies with community participation and strengthened governance mechanisms, this project offers a sustainable model for heritage protection in a region where cultural loss is accelerating. The paper demonstrates how digital innovation can bridge the divide between museum practice, community knowledge, and policy enforcement, ultimately contributing to a resilient, openly accessible digital archive that safeguards the cultural legacy of the Kalasha people for future generations. This approach aligns directly with the conference theme of Digital Innovations in Heritage Research, highlighting how digital tools can meaningfully address preservation challenges faced by marginalized communities.

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## 29. Preservation of Monuments of Ekamrakshetra

*Ranjit Kumar Das (Indian Institute of Technology Bombay)*

*Rasmita Mohanty (Tolani College of Commerce Mumbai)*

**Abstract:** Ekamra-Kshetra (modern Bhubaneswar, Odisha) stands as one of Odisha's five sacred kshetras and a pinnacle of Kalinga temple architecture. This paper examines its historical evolution from prehistoric settlements to a Shaiva center, identifies key conservation challenges like decay and urbanization, and evaluates structural and chemical preservation efforts by agencies such as the Archaeological Survey of India (ASI) and Odisha State Archaeology. It advocates for heritage zoning, public awareness, and UNESCO World Heritage nomination to ensure longevity for posterity.

**Keywords:** Ekamra-Kshetra, Bhubaneswar, monument conservation, Kalinga architecture, UNESCO heritage.

### Introduction

The conservation of Ekamra-Kshetra's stone monuments aims to maintain their structural integrity, mitigate decay, and prevent disintegration or disfigurement. These efforts, blending structural repairs with chemical treatments, address both natural and anthropogenic threats. This paper highlights major problems and solutions, grounded in the site's rich history, to

foster awareness among scholars, students of Ancient Indian History, Culture, and Archaeology. Bhubaneswar's monuments over 400 temples, caves, and inscriptions testify to millennia of cultural evolution, now imperiled by urbanization.

#### Historical Background of Ekamra-Kshetra

Ekamra-Kshetra, the ancient name for Bhubaneswar (Lat 20°15'N; Long 85°50'E), ranks among Odisha's five great kshetras: Shri-Kshetra (Puri, Vaishnava), Ekamra-Kshetra (Bhubaneswar, Shaiva), Arka-Kshetra (Konark), Viraja-Kshetra (Jajpur, Shakta), and Mahavinayak. Sanskrit texts like *Ekamra-Purana*, *Svarnadri-Mahodaya*, *Ekamra-Chandrika*, and *Kapila-Samhita* detail its temple origins, rituals, and merits (extending from Khandagiri in the west to Vahirodgesvara on Dhauligiri in the south).

Geographically, Bhubaneswar lies southwest of the Brahmani, Mahanadi, and Baitarani rivers amid laterite hills, perennial springs, and uncultivable jungles ideal for religious settlements. Its bracing climate and curative waters spurred growth as a Shaiva hub, rivaling national centers.

#### Architectural Significance

Bhubaneswar exemplifies Odisha's Kalinga style: curvilinear *deuls* (towers), *jagmohanas* (halls), and sculptural richness. Highlights include:

7th CE: Parasuramesvara (Ravana lifting Kailash); Svarnajalesvara (Rama vs. golden deer).

8th CE: Vaitala (Tantric Pasupata elements).

10th–11th CE: Muktesvara, Raja Rani, Brahmesvara; Lingaraja as architectural apex.

These, confined to "Old Bhubaneswar," draw tourists via proximity to Cuttack (438 km) and rail links.

#### Conservation Challenges

Monuments endure weathering, vegetation, disintegration, and urban sprawl, eroding aesthetics and threatening existence.

Natural Decay: Laterite vulnerability to moisture and salts.

Anthropogenic Threats: Rapid modernization post-capital status.

Historical Interventions: British-era repairs; post-independence acceleration by ASI (Bhubaneswar Circle), Odisha Archaeology, and INTACH.

#### Strategies and Solutions

##### Structural Conservation

Repairs stabilize fabrics, e.g., resetting stones and clearing debris.

##### Chemical Preservation

Modern preservatives reduce decay rates, applied selectively to minimize intervention.

Despite progress, efforts remain inadequate without local cooperation.

#### Recommendations and Conclusion

Declare Ekamra-Kshetra a Heritage Zone; expedite UNESCO nomination (initiatives underway). Accelerate ASI/state actions, bolster INTACH, and cultivate public awareness transcending caste/creed. We must preserve without altering character, handing intact patrimony to future generations. Collaborative stewardship will sustain this "eldorado" of Odisha's heritage.

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## 141. 3D Digital Reconstruction and GIS Mapping of Mahasthangarh: Integrating Archaeological Data for Virtual Preservation

Zillur Rahman (Ahsanullah University of Science and Technology)

This study explores the use of 3D digital reconstruction and GIS mapping to document, analyze, and preserve the archaeological site of Mahasthangarh in Bangladesh. Through the integration of drone photogrammetry, LiDAR scanning, and spatial analysis, a comprehensive digital model has been developed to visualize the site's urban and environmental evolution. The project aims to enhance understanding of the settlement's historical layout while supporting data-driven conservation planning. By combining diverse datasets into a single interactive platform, the reconstruction enables researchers to examine structural patterns, drainage systems, and long-term landscape changes. Beyond its academic value, the model provides an accessible tool for public engagement and heritage education. The study demonstrates how digital reconstruction can serve as both a research framework and a preservation strategy, offering a sustainable and collaborative approach to safeguarding South Asia's cultural heritage.

#### Context

Digital technology is rapidly changing how archaeology and heritage management are practiced across South Asia. Tools such as three-dimensional (3D) modeling and Geographic Information Systems (GIS) have opened new possibilities for documenting, analyzing, and protecting cultural heritage. Mahasthangarh, one of the earliest known urban archaeological sites in Bangladesh, provides an excellent opportunity to apply these technologies in reconstructing its ancient urban environment. By combining drone photogrammetry, LiDAR scanning, and GIS-based spatial analysis, researchers can generate accurate digital representations of the site's architectural and landscape features. These technologies enable not only more precise documentation but also innovative methods of preservation and interpretation. This study positions the Mahasthangarh digital reconstruction project within the wider field of computational archaeology, showing how virtual environments can safeguard threatened heritage while enhancing research, education, and public engagement (Bevan and Lake 2013).

#### Main Argument

This paper presents a structured digital workflow for reconstructing the archaeological site of Mahasthangarh through the integration of drone photogrammetry, LiDAR-based topographic modeling, and GIS spatial analysis. The goal is to create a detailed and dynamic digital model that allows for a more accurate understanding of the site's historical development and environmental context. Digital technologies now make it possible to document archaeological features with precision and to merge diverse datasets—ranging from architectural layouts to environmental and historical records—into a single, interactive platform (Kansa and Kansa 2021).

By generating a 3D reconstruction of Mahasthangarh, researchers can visualize spatial relationships across different periods of occupation and environmental change. This approach not only enhances archaeological interpretation but also provides valuable insights for conservation planning. For instance, high-resolution 3D and GIS data can help identify structural vulnerabilities, trace water drainage patterns, and model potential risks from erosion or vegetation growth. Predictive modeling based on these data enables proactive management and preservation of the site's physical integrity (Bevan and Lake 2013).

The integration of GIS within the reconstruction process also allows for layered visualization—combining historical maps, excavation records, and contemporary drone imagery. This spatial synthesis supports a more holistic narrative of Mahasthangarh's urban rise and decline, situating the site within broader regional patterns of settlement and landscape transformation.

Furthermore, the study emphasizes the need for open-access and interoperable data standards in archaeological research. Using transparent and reusable data formats ensures that digital heritage information remains accessible for future generations of researchers, heritage professionals, and the public (Kansa and Kansa 2021). Such an approach aligns with current best practices in computational archaeology, promoting collaborative research, reproducibility, and digital sustainability. Ultimately, this project



demonstrates how 3D modeling and GIS integration can serve not only as tools for documentation but also as frameworks for long-term heritage management and scholarly innovation.

#### Applications or Implications

The outcomes of this project have significance that reaches beyond the boundaries of Mahasthangarh, contributing to broader theoretical and methodological debates in digital and computational archaeology. The study demonstrates how digital reconstruction functions as both a research method and a heritage conservation strategy. By creating virtual replicas, endangered archaeological sites can be preserved digitally, ensuring that future scholars can study them even if their physical structures deteriorate. Moreover, the integration of geospatial data connects local archaeological studies to regional analyses, promoting comparative insights into early urban development across South Asia (Tripathi 2020).

Practically, the Mahasthangarh digital reconstruction model provides an engaging tool for education and public outreach. It allows museums, heritage sites, and virtual platforms to present immersive, interactive experiences that make archaeology more accessible to a wider audience. The model also assists heritage managers in identifying vulnerable zones and developing data-driven conservation plans. Ultimately, the integration of 3D modeling and GIS supports a sustainable, collaborative, and inclusive approach to archaeological preservation in South Asia (Kansa and Kansa 2021).

#### Illustration (Conceptual):

The digital reconstruction model integrates four data layers—3D Photogrammetry Surface Model (structural mapping), GIS Spatial Data ((Topography, Hydrology, Environmental Layers), Metadata Archive (historical maps and excavation records), and Integrated Digital Model (creating an interactive platform for visualization, analysis, and heritage conservation planning).

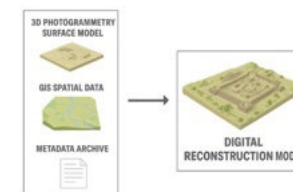


Figure 1. Conceptual Framework of the Mahasthangarh Digital Reconstruction Model

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### 183. A Mobile Application for Sex Estimation from Femur Measurements: A Practical Tool for Bioarchaeological Applications

Lanka Ranaweera (University of Kelaniya)

Eranda Cabral (University of Colombo)

D. M. P. V. Dissanayake (University of Kelaniya)

W. S. V. Lakshan (University of Kelaniya)

**Introduction:** Human skeletal remains represent invaluable findings within archaeological contexts, offering critical insights into the demographic and biological characteristics of past populations. Among the fundamental components of a biological profile, sex estimation plays a pivotal role in bioarchaeological research. The current gold-standard methods for determining sex rely primarily on well-preserved pelvic and cranial elements. However, in many archaeological contexts, these bones are often fragmented or absent, necessitating the use of alternative skeletal elements such as the femur, humerus, or tibia. To address this challenge, we aim to develop a mobile application through this research to facilitate accurate sex estimation using femoral measurements.

**Methods and materials:** This application, developed through research conducted at the Faculty of Medicine, University of Kelaniya, offers a user-friendly, data-driven approach to sex determination using osteometric parameters from the complete femur as well as its fragmentary components, the proximal end, shaft, and distal end using HTML, CSS, JavaScript, and rendered within a native mobile container. The selected variables were subjected to Linear Discriminant Analysis (LDA) and Logistic Regression (LR) to develop separate formulae for sex estimation.

**Results:** These validated formulae, derived from population-specific datasets, are integrated into the application, enabling users to input measurements and receive an immediate sex classification accompanied by accuracy indicators. The mobile app will be available for download from the Play Store under the name “Femur Sex Estimator.”

**Discussion:** This mobile app serves as a practical, reliable, and accessible analytical aid for research across multiple disciplines, including osteoarchaeology, forensic medicine, and biological anthropology. It enhances methodological standardisation and analytical efficiency, particularly in contexts where skeletal preservation is limited. Moreover, the application holds

significant potential for use within the Sri Lankan context and broader regional or global bioarchaeological arena.

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## 289. Digital Gandhara Project Preserving Buddhist Heritage in South Asia, Khyber Pakhtunkhwa, Pakistan

*Numan Anwar (directorate of archaeology and museum of khyber pakhtunkhwa Pakistan)*

The Gandhara region in Khyber Pakhtunkhwa, Pakistan, is renowned for its rich Buddhist heritage, boasting over 2,000 archaeological sites, including the UNESCO World Heritage Sites of Takht-i-Bahi and Taxila. The Directorate General of Archaeology and Museums, Government of Khyber Pakhtunkhwa, Pakistan, is committed to preserving these sites. However, the department faces challenges in excavating and protecting these sites due to limited resources and the threat of illegal excavation.

To address these challenges, the department has initiated the Digital Gandhara Project in collaboration with Harvard University. This project utilizes cutting-edge digital technologies, including GIS surveys, 3D laser scanning, and digital documentation, to preserve and promote the cultural heritage of Gandhara. The project aims to create an immersive online environment, allowing scholars and the general public to virtually experience the Buddhist sites of Gandhara.

The Digital Gandhara Project is a significant step towards preserving Pakistan's cultural heritage, particularly in the face of climate change and human-induced threats. By leveraging digital technologies, the project ensures the long term preservation and research of Gandharan art and culture, while also promoting global awareness and appreciation of Afghanistan's and Pakistan's shared cultural heritage

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Digital Gandhara - Harvard FAS CAMLab

Gandhara Archaeology A New Chapter to Technology

### 334. Mapping Economic Networks Through Metal: A Spatial Database Approach to Roman Coin Hoards in Early Historic Tamilakam

*Rizvan PS (University of Hyderabad)*

#### Introduction

Roman coin hoards found across hinterlands of early historic Tamilakam (present-day Tamil Nadu and Kerala, India) provide significant evidence from one side for trans-oceanic and from another side a regional networks and interactions during the Early Historic Period (circa 500 BCE–500 CE). Unlike port sites like Arikamedu, Pattanam, and Alagankulam, which received continuous development of interest, hinterland coin distributions remain less explored and fragmented across dispersed find reports, museum catalogues, and unpublished records.

This paper presents a computational framework addressing three questions: What are the spatial patterns formed by distributions of Roman coin hoards, and what do they tell us about trade route penetration and economic organization? How these coin hoard sites correlate with production centers,

settlements, and political capitals to shed light on redistribution networks? What will our quantitative analysis of denominations, quantities, and chronologies tell us about dating, kinds of activity, economic functions and significance of various zones and centers within maritime trade systems?

#### Methods and Materials

The study utilizes database construction, spatial analysis, and statistical pattern recognition. All published and known, but unpublished Roman coin finds from early historic Tamilakam are recorded in a relational database with standardized fields: location (with coordinates when possible), coin quantities, denominations (aureus, denarius), chronological range based on imperial portraits, find circumstances, and associated archaeological features. Data quality evaluation classifies records by spatial accuracy (exact coordinates, village-level, district-level) and chronological resolution, allowing their clear analysis of variable data quality.

GIS analysis maps georeferenced finds relation to environmental and archaeological features. Digital elevation models provide terrain data. Land-river routes (in macro-scale) and Paleo-channel networks (in micro-scale) based distribution model, built using satellite data, can be used to establish and evaluate the relationships between the distributions of coin hoards and the ancient river systems. Archaeological databases provided a comparative datasets for settlements, production centers, and political capitals. Kernel density estimation helped to recognize spatial clusters, and cost-distance analysis models which enabled the estimation of the most probable courses of ancient roads connecting individual coastal ports with inland regions.

#### Results

Such far-reaching multidisciplinary and the application of all these complementary methods enabled us to obtain unique and previously unattainable research results. Until now, the database compilation of documented over 40, most distinct Roman coin finds from hinterland contexts, combined with its spatial analysis reveals three concentration zones corresponding to major river systems: Vaigai basin near Madurai, part of Kaveri system around Karur

and Uraiyur, and Palar-river basin linking interior zones to Arikamedu. These patterns indicate rivers functioned as primary conduits for goods, and of course, coin movement from coastal entry points.

Correlation analysis shows systematic relationships between coin sites and other site types. Major production centers for iron, gemstones, beads (Kodumanal), and textiles show elevated coin presence. Also political capitals like Karur and Uraiyur appear as focal points for accumulation of numismatic finds, suggesting these centers controlled the flow of imported currency and its redistribution. Secondary settlements along river routes show moderate coin presence, consistent with transshipment functions.

Numismatic analysis reveals significant compositional patterns. Hoards near political capitals show higher proportions of gold aurei and silver denarii high-value denominations for large transactions and wealth storage. Production zones show more diverse assemblages indicate different economic functions and status levels. Chronological analysis indicates peak deposition during 1st-2nd centuries CE, with hinterland hoards showing chronological lag suggesting gradual inland penetration and multi-stage redistribution. Cost-distance modeling identifies probable routes connecting ports to hoard concentrations, which align with known archaeological sites, providing independent validation.

## Discussion

This computational approach demonstrates how systematic database construction coupled with spatial analysis transforms fragmented numismatic data into evidence for reconstructing economic networks. Spatial patterning reveals hierarchical redistribution moving currency from coastal entry points through political centers and production zones to interior regions. Strong correlation between coin distributions and river systems emphasizes practical trade logistics. Coins followed waterways because bulk export commodities followed the same routes.

Varying numismatic profiles suggest functional differentiation. High-value coins at political centers reflect large-scale transactions and elite wealth accumulation. Mixed denominations near production centers suggest diverse

economic activities. Chronological lag between coastal and interior hoards indicates multi-stage redistribution, challenging simplistic port-to-hinterland exchange models.

For computational archaeology, this research demonstrates analytical power combining database methods with spatial analysis. Relational database structure enables complex queries impossible with traditional catalogues. GIS integration transforms static find lists into dynamic spatial datasets amenable to statistical testing. This methodology is transferable to other regions with fragmented numismatic data. The study also highlights value of legacy archaeological data many included hoards were discovered decades ago. Systematically compiling and digitizing historical records demonstrates how computational approaches resurrect datasets, extracting new insights through methods unavailable at original publication.

Understanding economic integration into Indian Ocean trade networks requires examining hinterland dynamics beyond coastal ports. Coin hoards provide direct physical evidence for how Mediterranean wealth penetrated interior regions and circulated through local economies. Spatial analysis patterns indicate Tamilakam possessed sophisticated economic structures integrating foreign currency while maintaining regional organization centered on political capitals and production zones.

This research establishes that computational approaches can be essential for numismatic archaeology dealing with widely distributed finds. Database construction provides infrastructure for systematic analysis, while GIS enables spatial pattern recognition at landscape scales. Together, these methods transform coins from isolated curiosities into evidence for reconstructing ancient economic systems, revealing how early historic societies organized production, managed long-distance trade, and integrated external economic systems into regional structures.

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### 342. Geospatial Approaches to Cultural Heritage Documentation: Remote Sensing and GIS Applications in Burhanpur, India

*Manasi Patil (Independent)*

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has transformed the methodologies used for documenting, analyzing, and managing cultural heritage sites. This paper explores the application of RS and GIS technologies for mapping heritage sites in Burhanpur, a historically significant urban center in central India renowned for its Mughal-era monuments, religious architecture, and distinctive urban morphology.

Remote sensing provides the ability to capture large-scale, high-resolution spatial data through satellite imagery and aerial photography, enabling the detection of spatial changes and environmental impacts over time. GIS, on the other hand, allows for the integration, analysis, and visualization of multiple datasets including spatial, historical, and socio-environmental information within a single georeferenced framework. The combined use of RS and GIS facilitates a comprehensive understanding of the relationship between heritage sites and their surrounding landscapes, supporting decision-making processes related to conservation, land-use planning, and sustainable urban development.

Burhanpur, located in the state of Madhya Pradesh, India, serves as an exemplary case study for the application of these technologies. Historically significant as the Deccan headquarters of the Mughal empire and a major center of trade and culture, Burhanpur houses numerous architectural and archaeological monuments, including forts, royal baths, mosques, temples, and underground water supply systems. The town's intricate urban fabric reflects centuries of cultural evolution and historical layering. However, Burhanpur's heritage is increasingly at risk due to urban encroachment, infrastructural expansion, and inadequate management practices. The dense settlement pattern, combined with socio-economic pressures, poses serious challenges to the preservation of its built heritage and cultural landscape. Therefore, a spatially explicit and technologically grounded approach is essential for mapping and monitoring these heritage resources effectively.

This on-going research which is a part of the collaborative project 'Towards a National Cultural Landscape Information System: Mapping Heritage Sites for Inclusive Planning', led by the National Institute of Advanced Studies (NIAS), Bangalore aims to create a National Database of Cultural Heritage Landscapes for India along with highlighting the significance of adopting geospatial technologies not merely as technical tools but as integral components of a holistic heritage management strategy. Through the case study of Burhanpur, the paper attempts to demonstrate how open-source platforms, particularly QGIS can be employed to integrate remote sensing data with ground-based and historical information to develop a detailed, georeferenced inventory of heritage assets. The outcomes aim to contribute to a growing discourse on sustainable urban heritage management, offering practical insights and a replicable methodological framework for similar contexts across South Asia and beyond.



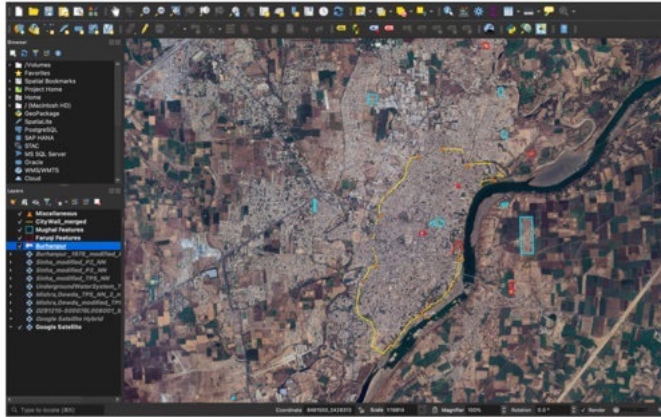


Fig. 1 - Mapped features in Burhanpur on QGIS

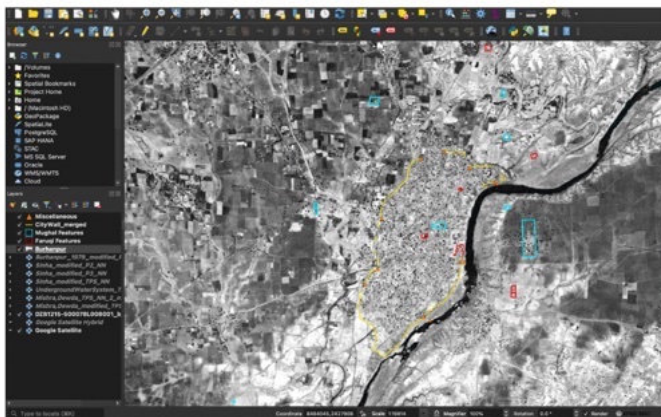


Fig. 2 - A 1970s Corona image georeferenced on QGIS

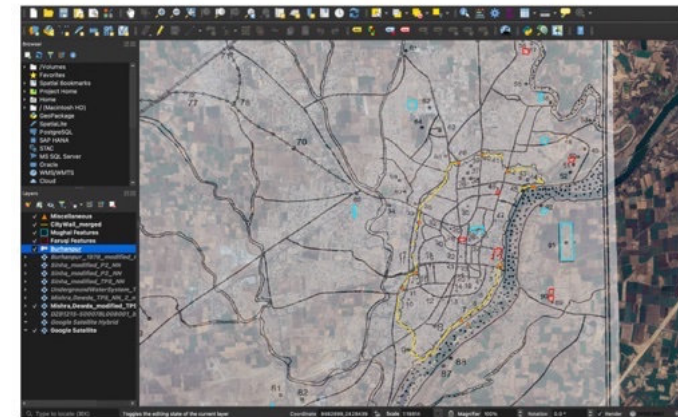


Fig. 3 - A map showing places of interest in Burhanpur (Mishra, Dewda, 2018) georeferenced on QGIS

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### 397. Building an R Shiny-based open archaeological database for the Indus Civilisation in north-western India: integrating spatial, chronological, and cultural data

*Ashish Verma (CSIC-IMF Barcelona)*

*Francesc C. Conesa (Social Sciences, Heritage, and Food (SOCIALPAT), IPNA-CSIC)*

*Rajesh SV (University of Kerala)*

*Abhayan GS (University of Kerala)*

*Juan José García-Granero (CSIC-IMF Barcelon)*

#### Introduction

Open-access archaeological databases are transforming how researchers manage, analyse, and share archaeological data, promoting transparency, reproducibility, and long-term preservation. Recent initiatives such as MedAfriCarbon database (Lucarini et al. 2020), the NeoNet dataset (Huet et al. 2022) and the 14Canarias database (Pardo-Gordó et al. 202) illustrate how large-scale digital infrastructures can centralise radiocarbon and archaeological information to reconstruct long-term social and environmental patterns. These platforms combine radiocarbon data with cultural and environmental attributes, offering dynamic and interactive tools for exploring settlement histories across time and space. However, despite similar needs, South Asia still lacks such integrative, open-access archaeological infrastructures, and data for many regions remain scattered across unpublished reports, journal articles, and institutional archives.

The region of Kachchh in north-western India, represents a critical frontier for understanding the emergence and transformation of the Bronze Age Indus Civilisation. Although decades of archaeological work have documented numerous sites, the data remain fragmented, making regional synthesis and comparative analyses difficult. We address this gap by developing the first

open-access and radiocarbon-based digital database and interactive web application for the archaeology of South Asia.

#### Methods

The database is built by integrating archaeological legacy data with new information from recent surveys. It includes sites spanning from the Early Harappan period (c. 3200–2800 BC) to the Medieval period. To do so, our recent fieldwork (2022–2025) has systematically revisited the location and cultural affiliation of several archaeological mounds reported in legacy datasets such as the Indian Archaeology Review series dating back to the 1950s. Each site record contains spatial coordinates, cultural attributions, material assemblages, and available chronological data. The system is developed entirely in R, with an interactive web interface built using the Shiny package to enable dynamic querying, filtering, and exploration. Spatial visualisation is implemented through a WebGIS interface created with the leaflet package, which displays archaeological sites interactively to explore their distribution across Kachchh through an intuitive browser-based map.

Our preliminary dataset currently includes c. 205 archaeological locations. Out of these, only 30 sites have yielded a total of 238 available radiocarbon dates. The latter are analysed using Bayesian chronological modelling to refine site-level occupation estimates and to produce Summed Probability Distributions that visualise regional temporal trends and phases of activity.

The work is carried out within the ongoing project BeforeIndus: Trade before urbanism: semi-nomadic pastoralism and the origins of the Indus Valley Civilisation (2024–2028), a joint initiative between the National Spanish Research Council and the University of Kerala.

#### Results

The database represents the first comprehensive and interactive synthesis of archaeological data from the Kachchh region, bringing together spatial, cultural, and chronological information within a single, open-access framework. Beyond its regional scope, our approach demonstrates the potential

of open-source and fully-reproducible computational workflows by integrating relational databases, visualisation, and probabilistic modelling.

The resulting digital platform will be openly available, enabling researchers to query, visualise, and download site information while providing a reusable platform that eventually will grow and integrate available radiocarbon datasets from other regions within the greater Indus River basin.

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### 419. Making the Absent Heritage Visible: Using Low-Cost and Portable Digital Tools to Document Heritage at Risk Sites in the Late Mughal Town of Farrukhnagar, India

*Simran Kaur (University of Exeter)*

In South Asia, the urban landscape is constantly subjected to the conflict between development and preservation of the historic fabric. Such a dichotomy between the needs of the present and the preservation of past is further complicated by a colonial and bureaucratic legacy of archaeological heritage management in India, set against a context of divisive histories and sectarianism. The monument-centric approach follows from its origins as a colonial project concerned with institutionalised documentation and cataloguing of local sites, customs, and people. The initial 'visual archives' of archaeological sites in India created in between the 18th and 19th centuries were primarily based on what the surveyor found to be architecturally important. As a result, non-classified archaeological sites in a dynamic urban landscape, even if excavated, have not been integrated in a proper heritage management and conservation plan.

In India, amongst the 10,000 sites that have been documented, only 3% are protected while only 0.025% are officially listed. In addition to the colonial legacy, the growing climate crisis and unregulated urban construction has further impacted the rate of loss of Heritage At Risk sites in India. Given the conflicting relationship between material conservation of the past, loss of heritage sites, and developmental needs, the heritage discourse merits an exploration of alternate ways of reconciling with the material past and change. Thus, the paper looks at how the integration of low-cost and portable digital tools such as iPhone LiDAR and photogrammetry into the Epi-collect 5 database can aid in digitally preserving Heritage At Risk sites (cf. Kędzierski et al., 2024; Soyloğlu et al., 2025; Zhang and Lan, 2025). Usage of such tools can enable an efficient, cost-effective, and accessible way of documenting heritage, especially in contexts where funding and time to access is restricted and the rate of destruction is alarmingly high.

The paper takes the case of the late Mughal (18th century CE) of Farrukhnagar in Haryana, once a prominent centre of salt trade in North India. Largely rendered invisible in official heritage listings during the colonial period, several 18th century CE built heritage structures in Farrukhnagar are being rapidly lost due to increasing urban growth and development pressure. It investigates whether 3D metric surveys taken on a LiDAR equipped iPhone 16 Pro

can be useful in undertaking the condition surveys of Farrukhnagar's heritage structures. iPhone LiDAR sensors can create digital models with an accuracy of about 1 to 4 meters. The paper looks at the use of four iOS applications such as Polycam, Sitescape, Scanniverse, and RealityScan for the generation of point-cloud data acquired from the LiDAR sensor. To test the potential of the digital models created using iPhone's LiDAR sensor and the point-cloud generation apps, the late Mughal palace complex of Sheesh Mahal was chosen. The iPhone LiDAR scans were taken sequentially across various parts of the Sheesh Mahal and then merged during post-processing. The open-source software CloudCompare (version 2.14) was used to validate the point clouds. Measurements were also taken using a BOSCH 150 M GLM Disto measure and the Measure feature on iPhone 16pro.

The second part of the project looks at the integration of these generated digital models onto an Epicollect5 database to make the data accessible to the wider public. Epicollect5 is an open-source software which enables the creation of customized databases for data collection. The form can record audio, video, locational coordinates, as well as any other data pertaining to a site. The software also enables multiple users to work on the same project at the same time. Thus, the digital models for the various structural aspects of the Sheesh Mahal were uploaded onto an Epicollect5 form alongside their condition survey metadata.

The results from the project discovered that iPhone LiDAR sensors are particularly accurate for small to medium scale heritage structures which are not complex in form. Accuracy of the point cloud and 3D model was impacted in large areas where the scan moving time was more. Misalignment was a common problem to be found with more complex or irregular structures. Thus, the accuracy of the point clouds was impacted by the size and shape of the structure, the application used, as well as the distance of measurement.

Portable and low-cost LiDAR smartphone scanners can be an effective tool to detect building conditions and vulnerabilities in heritage structures that are at an imminent risk of being destroyed. Despite certain anomalies, the smartphone scanners do enable the quick generation and sharing of the

digital models with other users. These models, when uploaded onto open-source databases such as Epicollect5, can provide a digital repository of Heritage At Risk sites available freely for researchers and the public alike. In some cases, the digital repository might be the only surviving data source for a heritage site which may cease to exist in the future. By digitally mapping sites that were traditionally excluded from official listings, the project contributes to the decolonisation discourse from a South Asian perspective. Access to the database and potential co-creation role for the local community of Farrukhanagar will further aid in making the local community equal stakeholders in the conservation and mapping of the heritage structures in Farrukhnagar. Such a collaboration with the community becomes very important if considering the long-term monitoring of Heritage At Risk sites.

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## S5: People from the Underground: Towards a Digital Archaeology of Subterranean Environments

*Konstantinos Trimmis, Australian Archaeological Institute at Athens*

*Ivan Drnić, Archaeological Museum in Zagreb*

*Sonia Machause Lopez, University of Valencia*

*Georgios Lazaridis, Aristotle University of Thessaloniki*

**Location:** Hörsaal 05

**Session Format:** Standard

Subterranean environments both natural – such as caves and rockshelters – and anthropogenic – such as catacombs, mines, tombs and so on – represent some of the most intriguing, complex, and methodologically challenging contexts for archaeological investigation. These enclosed and often disorienting spaces resist conventional archaeological approaches due to their spatial

configurations, microclimatic variability, and technological constraints. Despite this, underground sites have long been central to human history and memory, hosting an array of human activities functional, economic, and spiritual. Today, digital archaeology offers new and transformative means for their exploration, recording, and interpretation.

Until the beginning of 2011 the dominant way of mapping a cave and its finds that can be found in literature was based on the compass and tape (or Electronic Distance meters (EDM) technique (Stratford, 2011). In this case the measurements are recorded by hand and are transported to a database. The mapping error rate in this case is quite large even if the results of this method whenever it was applied were satisfactory (e.g. see Moyes, 2002; Stratford, 2011). However technological advances in surveying instruments, survey data analysis, LED lighting, digital photography, photogrammetry, cave specific software and recently handheld lidar sensors and Terrestrial Laser Scanners have revolutionised the way that we survey underground spaces and any archaeology within (see Trimmis 2018; and papers in Büster et al 2019 for reviews). Equally specialised software applications (such as Therion) and cave specific workflows for digital recording are also emerging and challenge the difficulties for an underground digital archaeology (see examples among others at Drnić et al 2018; Gazes et al 2024; Redovniković et al 2014)

This session invites contributions that engage with digital methods in the documentation and analysis of subterranean archaeological sites. The aim is to create a platform for sharing innovations, confronting methodological challenges, and envisioning future directions for digital subterranean archaeology. From high-resolution 3D modelling and GIS-based spatial analysis to sensor-based environmental monitoring and virtual reconstructions, the digital toolkit for exploring the underground is rapidly expanding. At the same time, subterranean fieldwork presents persistent hurdles: the absence of natural light complicates optical recording; the lack of GNSS and RTK reception demands novel solutions for georeferencing; and the volumetric nature of underground sites resists traditional 2D mapping approaches.

We especially welcome papers that address:

- Innovative survey techniques in low- or no – light and signal-deprived environments, such as SLAM-based LiDAR, paperless mapping methods, handheld photogrammetry, structured light scanning, and integrated inertial systems.
- Multi-sensor approaches that combine visual, thermal, acoustic, and environmental data to better understand underground contexts.
- Geospatial data management in complex 3D spaces, including workflows that integrate underground datasets into broader landscape-scale analyses.
- Human-environment interaction studies in caves and artificial underground sites using spatial statistics, movement modelling, and sensorial reconstruction.
- Challenges in visualization and communication, including virtual and augmented reality applications that allow audiences to access and experience subterranean spaces remotely.
- Interdisciplinary collaborations involving speleologists, geologists, engineers, and conservation scientists to solve recording and interpretation problems.
- Preservation and monitoring strategies enabled by digital documentation, particularly in response to climate change, tourism pressure, and development threats.
- Theoretical and epistemological reflections on how digital tools reshape our understanding of underground spaces as landscapes of material practice, memory, and myth.
- The session also encourages contributions from practitioners working in other disciplines that intersect with digital subterranean work, such as architectural documentation of tunnels or bunkers, forensic recording of underground conflict heritage, and digital humanities projects engaging with underground mythologies or urban substructures.

By bringing together an international community of researchers working “underground” this session seeks to advance a dialogue on how subterranean

spaces challenge and inspire digital archaeology, and how our tools and methods must evolve in turn. The discussion will contribute to developing best practices and shared standards for subterranean fieldwork and data integration, while also promoting critical thinking about the conceptual models we apply to space, visibility, orientation, and embodiment underground. Let’s illuminate the underground—digitally.

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<https://doi.org/10.1016/j.jasrep.2018.01.022>.

**10:30 – 10:50** 21. Illuminating the Underworld: An Integrated Digital Workflow for the Subterranean Necropolis of Saqqara  
*Matthias Lang\**; *Philippe Pathe\**; *Carmen Rac\**

*\* BCDH, Universität Bonn*

**10:50 – 11:10** 60. Smartphone LiDAR for Rock Art Caves Mapping: Accuracy Assessment through TLS in La Pileta (Málaga, Spain)  
*Rubén Parrilla (ICArEHB)*; *Daniel Antón\**; *Juan Mayoral\**; *María Simón-Vallejo\**; *Miguel Cortés-Sánchez\**

*\* Universidad de Sevilla*

**11:10 – 11:30** 93. Preserving the Past for the Future: Multimodal Digital Documentation of Actun Tunichil Muknal  
*Holley Moyes (University of California, Merced)*; *Dominique Rissolo (Qualcomm Institute; University of California, San Diego)*; *Scott McAvoy (University of California, San Diego)*; *Justin Simkins (Emescent Incorporated)*

**11:30 – 11:50** 107. An Innovative Remote Optical Workflow for Detecting Underground Features  
*Ioannis Lioumbas (Thessaloniki Water Supply and Sewerage Co. S.A.)*

**11:50 – 12:10** 144. Between Darkness and Data: Digital Approaches to Iberian Ritual Caves  
*Sonia Machause López\**; *Manuel Pérez Aixendri\**; *Agustín Díez Castillo\**; *Daniel Negueruela Villanueva\**; *Cristina Portalés Ricart\**

*\* University of Valencia*

**12:10 – 12:30** 159. Cave's air circulation modelling as a tool for spatial analysis – introductory remarks  
*Łukasz Czyżewski (Nicolaus Copernicus University)*

**12:30 – 13:30** Lunch break

**13:30 – 13:50** 256. Digitizing a whole Region: Archiving the Historic Mines of Silesia  
*Piotr Budzisz (Coal Mining Museum in Zabrze)*

**13:50 – 14:10** 271. An Integrated Multimodal Approach to the Digital Documentation and Spatial Contextual Analysis of Archaeological Cave Sites in Quintana Roo, Mexico  
*Dominique Rissolo\**; *Loren Clark\**; *Scott McAvoy\**; *Alberto Nava Blank (Global Underwater Explorers)*; *Julien Fortin (CINDAQ)*; *Samuel S. Meacham (CINDAQ)*; *Vid Petrovic\**; *Helena Barba Meinecke (INAH)*; *Silvina Vigliani (INAH)*; *Falko Kuester\**

*\* University of California, San Diego*

**14:10 – 14:30** 319. Data to Deployment: Operationalising 3D Datasets for Use in Virtual Reality Experiences: A Case Study on a Late Medieval Georgian Underground House



*Brian Armstrong\**; *Cassandra Kiely\**; *Jake Hubbert (University of California, Los Angeles)*; *Andrew Mahisa Halim\**; *Andrew Jameson\**; *Giorgi Bedianashvili (The Georgian National Museum)*

*\* University of Melbourne*

**14:30 – 14:50** 394. New data and research perspectives on the San Salvatore Hypogeum (Cabras, Sardinia)  
*Nicoletta Camedda\**; *Paola Derudas (Lund University)*; *Nicolò Dell'Unto (Lund University)*; *Danilo Marco Campanaro (Lund University)*; *Luca Cheri\**; *Ilaria Orri\**; *Anthony Muroi\**

*\* Fondazione Mont'e Prama*

**14:50 – 15:10** 412. Mining the scape – Laserscanning the archaeological mining landscape of Hallstatt  
*Matthias Kucera (University of Vienna)*; *Daniel Brandner (Natural History Museum Vienna)*; *Bernhard Groiss (Riegl LMS)*; *Bernd Paulowitz (World Heritage Salzkammergut)*

## 21. Illuminating the Underworld: An Integrated Digital Workflow for the Subterranean Necropolis of Saqqara

*Matthias Lang (BCDH, Universität Bonn)*

*Philippe Pathé (BCDH, Universität Bonn)*

*Carmen Rac (BCDH, Universität Bonn)*

### Introduction

The subterranean necropolis of Saqqara in Egypt presents a vast and complex landscape of ancient tombs. Within this context, the University of Tübingen's Saqqara Saite Tombs Project (SSTP) recently excavated Shaft K24, a 30-meter-deep and completely untouched communal burial complex (Hussein 2020). This excavation provided a unique opportunity for methodological innovation, as the intact, multichambered tombs present formidable documentation challenges (Lang, Kluge, and Hussein 2023). These challenges include narrow corridors, multilevel configurations, a complete absence of natural light, and the lack of any GNSS signal. Historically, the documentation of such contexts has been reliant on two dimensional methodologies, which inherently fail to capture their true volumetric and spatial relational complexities. Consequently, this paper addresses the central research question: How can a multisensor, integrated digital workflow overcome the unique constraints of subterranean Saqqara to produce a comprehensive, high fidelity 3D record of an active excavation, thereby facilitating new analytical insights into mortuary practices and conservation?

### Methods and Materials

The methodological foundation of this research is the comprehensive 3D digital documentation of the excavation of Shaft K24. Acknowledging that no single technology can capture the site's complexity, we employed a hybrid methodology to generate a 'digital twin' of the excavation process. A high accuracy geodetic control network, established via total station, provided the foundational spatial framework for all subsequent data acquisition. Large, open chambers and the main shaft were systematically recorded using a Terrestrial Laser Scanner (TLS) to generate a dimensionally precise point cloud, forming the backbone of the sitewide model. Concurrently, high resolution documentation of each archaeological layer, feature, and artifact in situ was accomplished utilizing near field photogrammetry. To overcome the challenge of total darkness, a camera mounted flash with a diffuser was used, a technique that both accelerated data acquisition and ensured evenly illuminated, color calibrated datasets. All resultant datasets were

coregistered within this control network, enabling the generation of discrete, sequential 3D models corresponding to each stratigraphic phase of the excavation.

## Results

The principal outcome of this methodology is a comprehensive, georeferenced, and multiscalar 4D dataset (3D space + excavation time) of the K24 tomb complex. This holistic dataset facilitated the virtual preservation of contexts that were physically unrecoverable, including severely decayed human mummies, thermo disintegrated wooden coffins, and other fragile organic materials. These sequential models constitute a highly detailed record of the archaeological process, enabling precise volumetric calculations, the derivation of high fidelity planimetric and sectional views, and the digital unwrapping of decorated surfaces. This procedure is particularly transformative for digital epigraphy, allowing for the creation of distortion free orthoimages that enhance the accuracy and legibility of intricate inscriptions during transcription. Furthermore, the integrated spatial record has elucidated complex architectural and depositional relationships between burial chambers that were previously unresolvable through traditional planimetric documentation.

## Discussion

The workflow developed at Saqqara constitutes a robust solution to the persistent challenges of subterranean archaeological recording, shifting the paradigm from static documentation to a dynamic record of the research process. Through the integration of TLS and near field photogrammetry, a strategy of 'preservation by documentation' was successfully implemented for irreplaceable archaeological information. The resultant 3D models function as powerful analytical instruments that facilitate novel avenues of inquiry into ancient Egyptian mortuary behavior, including the modeling of ritual kinematics and the analysis of microspatial relationships among burials, epigraphy, and associated material culture. Furthermore, these digital assets possess significant implications for cultural heritage management, public

engagement, and university pedagogy. They provide an essential record for conservation and hold transformative potential for immersive virtual reality applications, giving students the opportunity to visit the excavation and its various stages immersively. This enhances the accessibility of these otherwise unreachable spaces for both scholarly and public audiences. This research contributes to the formulation of best practices for digital subterranean archaeology. A critical component of this contribution involves addressing the challenge of long-term data sustainability; consequently, all resultant models and raw data from this multiterabyte dataset are being curated for perpetual preservation and scholarly access within the University of Bonn's institutional research data repository. (Lang and Salcedo Paparoni 2025).

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## 60. Smartphone LiDAR for Rock Art Caves Mapping: Accuracy Assessment through TLS in La Pileta (Málaga, Spain)

*Rubén Parrilla (ICArEHB)*

*Daniel Antón (Universidad de Sevilla)*

*Juan Mayoral (Universidad de Sevilla)*

*María Simón-Vallejo (Universidad de Sevilla)*

*Miguel Cortés-Sánchez (Universidad de Sevilla)*

Over the past decade, 3D technologies have changed how we document archaeological sites and caves (Antón et al. 2025). Among these technologies, LiDAR allows the creation of detailed 3D models of cave systems that can capture both complex morphologies and rock art graphisms with precision, moving away from the subjective interpretations of earlier methods. This technology can be understood as an important advance in documentation, facilitating spatial analysis, virtual exploration, and applications ranging from archaeology and geology to tourism and education.

However, documenting caves is a demanding task. Their intricate geometries and access difficulties have always a challenge for a correct coordinates adquisition. While Terrestrial Laser Scanning (TLS) delivers exceptional accuracy in these complex underground spaces, its high cost, bulky equipment, and logistical demands make it difficult to use in a wide-range project. Recent technological development has delivered smartphone LiDAR as a portable, affordable, and easy-to-use alternative (Antón et al. 2025), but its accuracy has been barely tested.

This research examines the geometric accuracy of low-cost smartphone LiDAR for cave documentation through systematic comparison with Terrestrial Laser Scanning (TLS). This study evaluates is this more accessible technology can deliver reliable measurements in archaeological and speleological contexts that require high precision.

A demanding test case has been used to assess its performance under real working conditions. La Pileta Cave (Málaga, Spain) constitutes one of Europe's most significant prehistoric art sites, containing 1236 catalogued motifs, of which 872 are attributed to the Paleolithic period, spanning approximately 30,000 years from the Upper Paleolithic through the Bronze Age. Nonetheless, recent research indicates that some graphic assemblages may extend the chronology into the earlier phases of the Upper Paleolithic in southern Iberia (Simón-Vallejo et al., 2024). Topographically, the cave comprises 2.5 kilometres of explored galleries forming a complex karstic system that presents considerable documentation challenges (Mayoral Valseira et al., 2017).

The methodology consisted of a systematic data acquisition and validation process. The main itinerary of La Pileta was initially scanned using smartphone LiDAR technology, which generates textured 3D meshes in real time. Subsequently, a TLS survey was conducted in a specific sector characterised by distinctive karstic morphologies and important Palaeolithic rock art panels. Both datasets were validated against a ground control point network established using a total station. Given the recognised geometric accuracy of TLS, this technique served as the benchmark for assessing smartphone LiDAR precision, thereby addressing the knowledge gap regarding the reliability of mobile LiDAR mesh data in applications requiring high measurement accuracy.

Results demonstrated that smartphone LiDAR is a viable technique for geometric recording in cave environments. While it exhibited lower absolute accuracy compared to TLS, it offered notable advantages in portability, data acquisition speed, and real-time visualisation. Significantly, smartphone LiDAR produced superior texture quality compared to TLS, a relevant finding for rock art panel documentation in karstic contexts. The optimal approach appears to combine both technologies: TLS for high-precision geometric

documentation and smartphone LiDAR for extensive coverage and enhanced texture capture.

Beyond the documentation produced at La Pileta, this research provides a systematic evaluation of smartphone LiDAR capabilities and limitations in challenging subterranean conditions characterised by absence of natural light, lack of GNSS signal, and complex three-dimensional geometries.

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### 93. Preserving the Past for the Future: Multimodal Digital Documentation of Actun Tunichil Muknal

*Holley Moyes (University of California, Merced)*

*Dominique Rissolo (Qualcomm Institute; University of California, San Diego)*

*Scott McAvoy (University of California, San Diego)*

*Justin Simkins (Emescent Incorporated)*

Actun Tunichil Muknal (ATM) is an ancient Maya ritual cave site located in western Belize, Central America that dates from the Preclassic to the Late Classic period (100-900 CE)(Moyes 2001). The site's importance lies in the excellent condition of its cultural remains as it is one of the few un-looted cave sites in the Maya region. It consists of a 5 km cave passage through which flows a perennial stream that culminates in a deep blue pool at the eastern entrance. Cultural remains were found in four major loci: the Main Entrance Chamber, the Sinkhole Tunnels, the Stela Chamber and the Main Chamber-- the most intensively and extensively area used by ancient people. Located 500 meters from the eastern cave entrance, where a high-level passage splits off from the main passageway, it is accessed via a climb to a constricted entryway. This area contains over 1500 unique artifacts as well as the remains of at least 21 individuals. Recorded from 1996-1998 by the Western Belize Regional Cave Project, the project produced detailed maps of archaeologically rich areas, conducted excavations, and analyzed human remains. The site was then opened for tourism following these investigations. Since then, it has become one of the most popular tourist venues in Belize. Today, the site is being preserved as a living museum. It is among the most visited archaeological caves in the Maya area and is well known for its striking physical characteristics and geological formations as well as its remarkably intact cultural deposits. Impacts from tourism and natural causes place this cave at risk and some damage has already occurred, though careful curation and regulated tourism has minimized these impacts. Although the cave has been mapped using traditional cave mapping techniques, new technology provides an opportunity to create a 3D detailed digital twin to record and archive the cave as it exists now providing digital preservation in a changing environment.

In partnership with the Belize Institute of Archaeology, a collaborative program of scanning was conducted in the summers of 2023 and 2024, using

complementary imaging modalities across scales and resolutions (Rissolo et al. 2025). These included mobile LiDAR – which was ideally suited to the complex, partially flooded passageways and high, narrow chambers of the cave – as well as high-resolution structured-light scanning (of individual objects and features) and photogrammetry. Particular attention was given to the human skeletal remains and ceramic vessels that lie within close proximity to visitor routes within the cave.

To provide a record of the cave's geometry, the Hovermap (by Emesent) was employed. This unit pairs a Velodyne LiDAR with a proprietary SLAM (simultaneous localization and mapping) algorithm and processing system that can be used in two modes: a handheld device that scans while walking or one in which the scanner is mounted on a customized multirotor UAV. This allowed us to conduct progressive scanning while walking through constricted or confined spaces with the unit in-hand and also to fly the unit through cavernous areas and to hard-to-reach spaces (Moyes et al. 2023). Ultimately, a 3D “digital scaffold” (created via the processing and alignment of mobile-LiDAR generated point data) supports the integration of data from complementary imaging modalities.

For highly detailed precision, integral to our multimodal and multi-scalar workflow is the Artec Leo mobile structured-light scanner. Artec scanners are the standard for osteological research and offer certified levels of precision and accuracy that enable morphometric and taphonomic analyses of scanned skeletal elements. Image acquisition for photogrammetry followed standardized techniques and guidelines. Though the focus was on specific features, such as ceramic vessels or human skeletal remains, care was taken to capture portions of the surrounding area or cave context to facilitate eventual co-referencing with the mobile LiDAR-generated point cloud. Since wider areas can more reasonably be captured via photogrammetry (rather than structured-light scanning), the technique served as a “middle space” (in terms of scale and fidelity) between mobile LiDAR and structured light. Using these technologies, images collected at different scales were integrated into a single 3-dimensional interactive digital twin of the cave system.

The result of our integrative, multimodal approach is a fused multi-resolution digital twin of ATM. These 3D data not only serve as an accurate geometric record of the cave and its contents but will enable researchers to better visualize spatial contextual relationships and facilitate taphonomic analyses across scales. The comprehensive mobile-LiDAR mapping campaign has allowed us to visualize and appreciate, for the first time, the size and complex morphology of the cave itself – in 3D. Our methodology has essentially made possible a degree of immersion that reveals or communicates certain phenomenological aspects of the cave as well. We are currently working towards an accessible, online, interactive version of the digital twin, which will be tailored for guides and the interested public.

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## 107. An Innovative Remote Optical Workflow for Detecting Underground Features

*Ioannis Lioumbas (Thessaloniki Water Supply and Sewerage Co. S.A.)*

## Introduction

The identification of buried structures remains one of the most persistent challenges in both archaeological and engineering contexts. Traditional field and geophysical surveys, although accurate, are often costly, time-consuming, and dependent on local accessibility, soil conductivity, or illumination stability. In recent years, advances in optical remote sensing—particularly the increasing spatial and radiometric resolution of satellite and drone imagery—have enabled the detection of subtle surface anomalies that indirectly reflect subsurface features. Recent research, such as that by Abate et al. (2020) and others, has shown that multi-temporal optical observations can reveal archaeological traces that become visible only under specific environmental or seasonal conditions. This spatio-temporal approach has highlighted how buried structures may influence vegetation or soil behaviour differently over time, allowing their intermittent detection across certain months or landscapes. These studies established the value of long-term optical monitoring for cultural-heritage and landscape interpretation. However, while they recognized the temporal variability of such phenomena, they did not propose a systematic way to combine these changing surface expressions into a unified, reproducible representation. To address this gap, the Thessaloniki Water Supply and Sewerage Company (EYATH SA) has developed and patented a novel remote optical workflow (Lioumbas et al. 2025) that algorithmically integrates multi-temporal, geo-referenced imagery into a single synthetic anomaly map. By quantifying and enhancing recurrent colour variations through standardized processing, this method transforms sporadic visual observations into a coherent analytical framework—offering a non-invasive, low-cost, and transferable tool for detecting subsurface archaeological and engineering structures.

## Methods and materials

The method operates on the principle that subsurface discontinuities subtly modify surface moisture and reflectance patterns, which, when consistently sampled and normalized over time, can be quantified as recurring spatial

signatures. The procedure consists of five main phases. First, multi-temporal optical images covering identical coordinates are collected and atmospherically corrected to ensure radiometric comparability between dates. Second, a uniform grid of sampling points is automatically generated within the study area, with optional “enhancement” points placed around each node to capture local variability. Third, for every image and grid point, pixel values in the visible and Near Infrared spectrum are extracted and converted to grayscale numeric data. Fourth, the temporal sequence of grayscale values is normalized by comparing local to cumulative means, and an exponential enhancement function is applied to accentuate relative deviations associated with potential subsurface influence. Finally, all normalized values are visualized in a composite synthetic map where brightness and point size represent the magnitude of the normalized response.

The workflow was applied to two representative case studies. The first validation site, located along the Aravissos water-supply pipeline, was selected as a controlled engineering testbed for the patented workflow. The Aravissos pipeline, constructed between 1975 and 1978, extends approximately 52 km from the Aravissos springs at Mount Paiko to the Gallikos River plain. This gravity-fed conduit, composed of prestressed concrete reinforced with helical and longitudinal steel and buried at a depth of 2–2.5 m, provides about 35 % of Thessaloniki’s potable-water demand. The second case study, at the broader archaeological site of Pella in northern Greece, was conceived as a complementary validation environment under different expected underground structures. Archaeological sites provide ideal testing grounds for such methodologies, as they encompass variable soil types, surface textures, and depths of known buried structures previously documented through magnetic and resistivity surveys. Validating the workflow in these contexts is essential for assessing its sensitivity to different physical parameters—such as soil composition, moisture content, and burial depth—and for determining how consistently the algorithmic enhancement and normalization stages respond across distinct environmental and spectral regimes. The preliminary analyses presented here therefore represent only an initial stage of archaeological validation. A broader series of tests across multiple sites,



encompassing diverse geomorphological and spectral settings, is required to extend the validation base and encourage comparative applications within cultural-heritage contexts.

## Results

The application of EYATH's patented optical workflow yielded consistent and verifiable results across both test sites. In the Aravissos pipeline, the multi-temporal analysis transformed visually featureless agricultural imagery into a synthetic map exhibiting a continuous high-intensity linear anomaly precisely aligned with the known buried conduit. The enhanced grayscale response is interpreted as the surface manifestation of moisture redistribution and compaction contrasts along the pipeline. The detection, achieved without field calibration or spectral filtering, demonstrates the workflow's ability to identify linear subsurface infrastructure solely through temporal optical normalization. At Pella, the detected optical anomalies coincide spatially with areas previously investigated through combined surface and geophysical surveys (Tsigarida et al. 2018; in print, with earlier references), confirming the complementarity between optical temporal analysis and ground-based methods. This correspondence supports the method's sensitivity to shallow structural heterogeneities beyond hydrological effects and indicates that optical temporal variability can reveal stable archaeological patterns under different soil and vegetation conditions.

Together, these results demonstrate that the workflow is reproducible across contrasting geomorphological and subsurface contexts—ranging from buried water pipelines to potentially buried man-made constructions of archaeological significance. The coherence between optical anomalies and independently validated subsurface data substantiates the method's diagnostic robustness. Further applications across additional sites will refine detection thresholds and assess spectral–environmental dependencies, but the present findings already confirm the workflow's potential as a unified, low-cost approach for mapping buried linear and discrete structures.

## Discussion

The initial applications of EYATH's optical workflow indicate promising reproducibility across distinct environments, yet its broader validity requires systematic testing under more diverse conditions. Archaeological and engineering contexts represent only two endmembers within a wider spectrum of subsurface variability. To establish the workflow as a standardized optical diagnostic tool, it must be evaluated across multiple sites that differ in soil composition, texture, moisture regime, vegetation cover, and burial depth. Such comparative testing will allow quantitative assessment of detection thresholds, false-positive rates, and environmental sensitivities, providing a statistically grounded measure of reliability. Integration with established geophysical datasets—magnetometry, resistivity, or GPR—will further clarify the causal mechanisms linking optical anomalies to subsurface structures. Expanding the validation dataset is therefore essential to transform this method from a context-specific proof of concept into a generalizable framework for non-invasive subsurface detection in both engineering and archaeological domains.

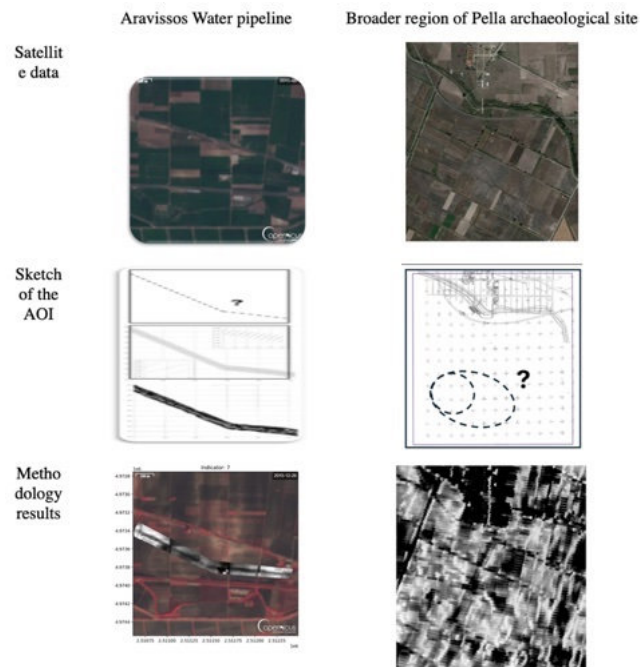


Figure 1. Comparative application of the EYATH patented remote optical workflow in two contexts: (left) the Aravissos water pipeline and (right) the broader archaeological site of Pella.

Top row: multi-temporal satellite imagery of the study areas (Copernicus and Google Earth).

Middle row: sketches of the areas of interest (AOI); the broader archaeological region of Pella map indicates archaeological features documented by (Tsigarida et al. 2018; in print, with earlier references).

Bottom row: synthetic maps generated by the patented workflow, showing enhanced grayscale anomalies. A clear linear signal corresponds to the buried water pipeline at Aravissos, while in the broader archaeological site of Pella, geometric responses probably indicate subsurface archaeological structures.

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## 144. Between Darkness and Data: Digital Approaches to Iberian Ritual Caves

*Sonia Machaue López (University of Valencia)*

*Manuel Pérez Aixendri (University of Valencia)*

*Agustín Díez Castillo (University of Valencia)*

*Daniel Negueruela Villanueva (University of Valencia)*

*Cristina Portalés Ricart (University of Valencia)*

Caves have long been regarded as symbolic and liminal spaces. During the Iberian Iron Age (6th–1st centuries BCE), certain natural cavities, often located far from settlements, were used for ritual purposes, especially between the 5th and 4th centuries BCE. The archaeological record preserved in these sites—ceramics, faunal remains, charcoal, metals, and, in some cases, human bones—reveals structured depositional patterns and ritualized gestures carried out within these subterranean environments.

Recent studies have highlighted the heterogeneity of practices and depositional dynamics associated with these caves (Machaue 2019). Over the past decade, a new generation of interdisciplinary projects has revitalized the study of Iberian ritual caves through digital and sensory methodologies. In the Valencian region, Cueva del Sapo (Chiva, Valencia) and Cueva Merinel (Bugarra, Valencia) stand out as key examples. Both are located within the

southern territories controlled by the Iberian city of Edeta (Tossal de Sant Miquel de Llíria) (Machause & Díez 2022; Machause & Skeates 2022). Excavations conducted since 2018 at El Sapo and since 2024 at Merinel demonstrate their exceptional potential for understanding ritual practices, as well as the symbolic and territorial organization of the Edetan landscape during the Iron Age.

This paper presents the digital workflow developed within the project *Deep in Caves: Iberian Rituality in Context* (Generalitat Valenciana: CIGE 2022/94), now integrated into the transdisciplinary project *RITCONTACT: A Journey Between Two Worlds. Caves, Ritual Practices and Symbolic Landscapes in Iberian Societies* (Fundación Ramón Areces). The approach combines three main strategies: high-resolution documentation (photogrammetry and LiDAR), digital recording during excavation, and immersive virtual valorisation. Together, they address the specific methodological challenges of underground archaeology—low-light conditions, lack of GNSS signal, spatial complexity, and conservation fragility—while exploring the sensory and symbolic dimensions of Iberian rituality.

### 1. Digital Documentation and Multi-sensor Analysis

At Cueva Merinel and Cueva del Sapo, high-resolution 3D documentation was undertaken for the first time using a fully paperless workflow. Laser scanning, carried out by Global Mediterránea, established the spatial framework for precise georeferencing of excavation trenches, integrated within ETRS89-based coordinate systems. These 3D models are then connected to relational databases incorporating topographic, stratigraphic, and descriptive data, generating a holistic and dynamic documentation system.

Beyond accurate spatial recording, these datasets support multi-scalar and multi-sensor analyses that integrate GIS-based spatial modelling, environmental parameters (light, humidity, temperature), linked to sensory variables. This digital and relational approach enables the identification of depositional areas, ritual zones, and symbolic compartmentalization within the caves, contributing to the interpretation of the cognitive and social dimensions of Iberian rituality.

### 2. Digital Recording in the Field

Each stratigraphic unit (SU) is digitally recorded before and after excavation using both photogrammetry and handheld LiDAR scanning. Data processing is performed directly on site, where 3D models are aligned and georeferenced using software such as MeshLab and CloudCompare. The resulting digital terrain models (DTMs) and orthophotos replace traditional photography and drawing, producing a high-resolution 3D stratigraphic sequence. This approach ensures reproducibility, precision, and the long-term preservation of contextual data—key aspects in subterranean archaeological recording.

### 3. Virtual Valorisation and Immersive Communication

Digital technologies open new possibilities for the preservation and communication of fragile underground heritage. The creation of a digital twins of El Sapo and Merinel through photogrammetry and LiDAR safeguards their current condition and makes these inaccessible ritual spaces available to wider audiences, from any location and at any time. Future developments within the *RITCONTACT* project include interactive 3D models and immersive virtual reality experiences designed to recreate the sensory conditions of Iberian ritual acts.

These environments will combine stratigraphic data, material analyses, environmental records, and interpretive reconstructions—such as light simulation, acoustic modelling, and virtual agents—to generate scientifically grounded yet experiential narratives. By merging digital precision with sensory imagination, these reconstructions seek to convey how subterranean spaces shaped Iberian ritual experiences and cosmologies.

Ultimately, the integration of photogrammetry, LiDAR scanning, GIS-based analysis, and immersive visualization represents a methodological and conceptual advance for underground archaeology. It fosters a more inclusive and sustainable practice—one capable of preserving, interpreting, and communicating the invisible heritage of the past. Between darkness and data,

RITCONTACT explores the boundary between materiality and meaning, the ancient and the digital, the subterranean and the virtual.

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### 159. Cave's air circulation modelling as a tool for spatial analysis – introductory remarks

*Łukasz Czyżewski (Nicolaus Copernicus University)*

Previous research related to air circulation in cave structures has been based on a general, simplified model of the movement of warm and cold air masses within an enclosed space. This research also links the distribution of potential hearths and possible smoke accumulation (Kedar and Barkai, 2019, Kedar, Kedar and Barkai, 2022) to the aforementioned general model, relying on the current morphology of cave structures. While this model is useful, it does not resolve several important issues. It focuses on the present-day shape of the chambers and, by assuming only the current entrance locations, reconstructs an air circulation model relevant only to the most recent periods of habitation.

Based on these experiences, we are discussing a more precise model of air circulation analysis for the Biśnik Cave – a multi-phase site with a complex spatial structure (several irregular chambers, multiple levels of entrance openings and potential ventilation points). The goal is to approximate historical phases of air circulation, based on the spatial analysis of the distribution of the noted hearths, to demonstrate possible airflow patterns and possibly identify yet undiscovered entrances that may have further shaped the usable space.

These considerations, along with the research plans presented here, contribute to the broader discussion on the possibilities of detailed modelling of air circulation in prehistoric habitation spaces, grounded in specific theoretical assumptions.

### 256. Digitizing a whole Region: Archiving the Historic Mines of Silesia

*Piotr Budzisz (Coal Mining Museum in Zabrze)*

#### Introduction

The Mining Documentation Hub (MDH) at the Museum of Coal Mining in Zabrze is currently undertaking one of the largest subterranean digitization projects in Europe: the creation of a comprehensive digital archive covering over 60 historically documented coal mines of the Silesia region. Each mine comprises an average of 90–110 kilometres of underground workings, together forming an immense and highly fragmented cultural landscape.

The project's aim is to document, preserve, and interconnect the surviving material, spatial, and archival traces of Silesia's mining past - both above and below ground - within a unified digital framework. While individual 3D scanning of underground heritage is increasingly common, applying these methods at a regional scale poses unique technical and conceptual challenges. The primary research question guiding this work is: How can digital archaeology be scaled to document, manage, and interpret a vast network of

interconnected subterranean environments while maintaining scientific accuracy, interoperability, and cultural relevance?

#### Methods and Materials

Daily work within the MDH combines archival reconstruction and multi-scale 3D documentation.

Archival activities include the recovery, digitization, and metadata cataloguing of historic mine maps, engineering drawings, photographs and other acquired documentation spanning from the beginning of 19th century to the late 20th century. These materials are integrated into a spatial database to establish a reference model for contemporary field documentation.

Field documentation employs a range of complementary technologies:

Terrestrial Laser Scanning (TLS) for large chambers and surface structures.

Handheld and SLAM-based LiDAR for narrow and inaccessible workings.

Close-range photogrammetry for structural and artifact-level recording.

Structured-light scanning for small-scale details.

Inertial and optical hybrid positioning workflows to compensate for the absence of GNSS/RTK underground.

Captured data are processed through a tiered data pipeline, combining automated point cloud cleaning, semantic segmentation, and georeferencing against archival baselines. All datasets are curated in a cloud-based geospatial repository designed for interoperability with GIS, CAD, and 3D web visualisation tools.

#### Results

The current stage of work has produced a regional reference database integrating archival and digital datasets for eight pilot mines. The combined dataset already exceeds hundred terabytes, including raw LiDAR, photogrammetric meshes, vector maps, and environmental metadata.

Preliminary results show that hybrid georeferencing significantly reduces cumulative drift in long underground corridors, achieving average alignment errors below 10 cm even in multi-kilometre traverses. Archival overlays allow reconstruction of now-collapsed workings and validate the historical extent of mine development.

This process has also yielded standardised documentation templates and fieldwork kits that allow consistent data acquisition across teams. The same pipeline can be scaled to cover additional mines, allowing the construction of a unified “digital stratigraphy” of the Silesian mining landscape - from shaft to region.

#### Discussion

Working at this magnitude forces digital archaeology to confront both logistical and epistemological limits.

Logistically, the challenge lies in coordinating multidisciplinary teams across dozens of partially accessible sites, ensuring safety, maintaining consistency in scanning conditions, and handling extreme data volumes. Epistemologically, the question arises: what constitutes a “site” when the underground forms an interconnected network of hundreds of kilometres?

This project reframes digital documentation as a regional-scale archaeological practice, one that blends techniques from heritage science, mining engineering, and informatics. The outcomes not only advance heritage preservation but also enable virtual exploration, research reuse, and educational outreach, linking industrial history with emerging digital platforms such as VR, GIS-based storytelling, and interactive public archives.

Ultimately, archiving the entirety of Silesia’s subterranean legacy demonstrates how digital archaeology can transcend the boundaries of excavation and site-based research, transforming vast industrial voids into accessible, interpretable, and sustainable cultural datasets.

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## 271. An Integrated Multimodal Approach to the Digital Documentation and Spatial Contextual Analysis of Archaeological Cave Sites in Quintana Roo, Mexico

*Dominique Rissolo (University of California, San Diego)*

*Loren Clark (University of California, San Diego)*

*Scott McAvoy (University of California, San Diego)*

*Alberto Nava Blank (Global Underwater Explorers)*

*Julien Fortin (CINDAQ)*

*Samuel S. Meacham (CINDAQ)*

*Vid Petrovic (University of California, San Diego)*

*Helena Barba Meinecke (INAH)*

*Silvina Vigliani (INAH)*

*Falko Kuester (University of California, San Diego)*

The now submerged and semi-submerged cave systems of the eastern Yucatan Peninsula, Mexico, provide access to well preserved Late Pleistocene and Early Holocene deposits that reveal a wealth of information about the human prehistory and paleobiogeography of the region (Chatters et al. 2017). Ongoing interdisciplinary research efforts aim to identify and reconstruct the processes that have formed and transformed these subterranean sites over

millennia. In addition to ongoing studies involving evidence of human activity, human skeletal remains, and diverse assemblages of Pleistocene-Holocene fauna and botanical deposits, the development of digital workflows enables virtual access to remote sites.

Rather than functioning simply as 3D models, multimodal and multiresolution digital twins enable virtual taphonomic analyses across scales – allowing domain experts to annotate, segment, extract, measure, and compare, while taking advantage of surface or volumetric views afforded by complementary imaging and remote sensing modalities. These include in situ single camera photogrammetry; integrated multicamera photogrammetry; structured-light scanning; SLAM-based LiDAR; ground penetrating radar; ex situ photogrammetry; X-Ray; and CT scanning.

Additionally, native image files corresponding to point regions can be readily and simultaneously consulted as users virtually access the caves. The interactive, point-based visual analytics workflow has proven to be especially empowering for researchers unable to otherwise physically access deep and remote underwater sites. In practice, team researchers have used the digital twins to select specimens for recovery, collaboratively plan the recovery process, and design and develop custom recovery hardware and techniques without ever seeing the deposits in person.

Current studies also address how humans and megafauna accessed and navigated through the extensive, anastomosing cave passages of the central coastal region of Quintana Roo during the Late Pleistocene to Early Holocene. By evaluating cave entrance and passage morphologies relative to the anatomy of extinct species found in these environments – giant ground sloths, bears, saber-toothed cats, proboscideans – we can more accurately reconstruct (or hypothesize) faunal entry and movement (Clark et al. 2025). Ancient human visitors carried light and were able to negotiate obstacles via ropes, ladders, and alterations to the cave interiors. Now flooded evidence of subterranean activities, such as ochre mining and water collection, are



abundant and have been digitally documented and integrated into the spatially linked database and digital twin.

Later Maya use of cenotes and dry cave systems in Quintana Roo is ubiquitous. The presence of ancient Maya shrines, offerings, and rock art in caves serves as unequivocal evidence for the ritual appropriation of these subterranean spaces and their significance with respect to Maya religious practice. Ongoing study of the miniature masonry temples and altar features in the region's caves reveals a strong stylistic and likely functional correspondence between these structures and their terrestrial counterparts at Postclassic sites like Tulum, Tanchah, and Xamanha. The digital documentation campaign and multimodal data fusion efforts extend to these Maya features and sites as well – linking regional subterranean spaces to their larger temporal and topographic contexts (Rissolo et al. 2024).

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### 319. Data to Deployment: Operationalising 3D Datasets for Use in Virtual Reality Experiences: A Case Study on a Late Medieval Georgian Underground House

*Brian Armstrong (University of Melbourne)*

*Cassandra Kiely (University of Melbourne)*

*Jake Hubbert (University of California, Los Angeles)*

*Andrew Mahisa Halim (University of Melbourne)*

*Andrew Jameson (University of Melbourne)*

*Giorgi Bedianashvili (The Georgian National Museum)*

Archaeological interpretation has long sought to recover the lived experience of past societies through material remains. Yet even the most detailed excavation or static 3D reconstruction cannot convey the phenomenological dimensions of inhabiting space, experiencing light, sound, temperature, and movement. To transcend this critical limitation and interrogate the fundamental difference between architectural abstraction and the felt experience, this project operationalises immersive Virtual Reality (VR) as an embodied spatial medium for phenomenological investigation (Kelly 2023).

This research introduces a VR project focused on the digital reconstruction of a Late Medieval Georgian Darbazi dwelling, a semi-subterranean

vernacular house characterized by its distinctive wooden roof (Sumbadze 1984), called gvirgvini (Figure 1A). Primarily located in the rugged Meskheti region of Southern Georgia, these structures represent a sophisticated architectural tradition that is now often inaccessible, partially lost, or suffering from poor conservation, necessitating new methods for preservation and cultural interpretation.

Moving beyond traditional ocularcentric representation and static 3D visualisations, this project employs high-resolution 3D datasets to create an embodied experiential medium. The immersive environment will be deployed through head-mounted display (HMD) technology, enabling full spatial embodiment and interaction. This choice of medium allows users to experience the reconstructed Darbazi dwelling at a 1:1 scale, fostering a sense of presence and bodily awareness that static visualisations cannot achieve. By leveraging a HMD based VR, the project seeks to replicate the sensory and spatial dynamics of subterranean habitation, offering an interpretative tool that is both rigorous and experientially rich. The primary aim is to investigate the unique phenomenology of dwelling in a semi-subterranean space. The VR environment is designed to modulate the user's perception of time and evoke the profound cultural memory and atmosphere of this place by strategically choreographing key architectural features, such as the experiential contrast between the karapani, the constriction of the subterranean entrance (Figure 1B), and the symbolic vertical light shaft of the erdik (Figure 1A). This methodology aims to integrate archaeological science with architectural theory and digital innovation to transform heritage interpretation and educational outreach.

Archaeological and digital survey data collection occurred in July of 2025. This includes large-scale 3D datasets captured using a Nikon D850 DSLR for high-resolution photogrammetry and a GeoSLAM ZEB Revo scanner for LiDAR acquisition. Photogrammetric processing was conducted in Agisoft Metashape, producing detailed textured meshes of the wooden ceiling and other key architectural components, such as the subterranean entrance,

underground tunnel (darani), and hearth features in each room. We have successfully archived low-resolution processed versions of five rooms, along with scans of the house layouts and 4K drone footage. This comprehensive data provides the foundational material required for the detailed digital reconstruction of the physical architecture and the documented state of decay, serving as an urgent call for intervention.

For immersive deployment, the VR environment is being developed in the Unity Game Engine, enabling real-time rendering and interactive features tailored for HMD platforms. In parallel, we are actively workshopping a storytelling scenario with our Georgian collaborators to ensure cultural authenticity and narrative depth, embedding local voices and traditions into the VR experience.

As we move toward the next critical phases of digital reconstruction and immersive development, this presentation serves as a moment of expert consultation. Our project stands at a critical juncture: armed with archaeological and digital data, we face the technical and theoretical challenge of crafting an embodied VR experience that authentically interprets this unique Georgian heritage. By combining archaeological science, advanced computing, and phenomenological design, we believe this initiative can bridge the gap between abstract data and qualitative lived experience. We invite the expertise of this conference to help us define the necessary steps to move from data to deployment and realize the full scholarly and cultural impact of this virtual re-creation.

Evaluation is also central to methodological design. The project will incorporate user-testing protocols targeting school groups and museum visitors to assess learning outcomes, emotional engagement, and spatial comprehension. We aim to develop analytics dashboards to capture quantitative and qualitative data, including duration of engagement, navigation patterns, and self-reported affective responses, allowing for evidence-based evaluation of

how immersive technologies influence understanding and empathy in heritage contexts.

Keywords: Virtual Reality (VR), 3D Reconstruction, Phenomenology, Cultural Heritage, Georgian Architecture, Digital Preservation



*Figure 1A: Inside the Darbazi dwelling with its distinctive wooden roof and light opening*

*Figure 1B: Semi-Subterranean entrance of the Darbazi*

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### 394. New data and research perspectives on the San Salvatore Hypogeum (Cabras, Sardinia)

*Nicoletta Camedda (Fondazione Mont'e Prama)*

*Paola Derudas (Lund University)*

*Nicolò Dell'Unto (Lund University)*

*Daniilo Marco Campanaro (Lund University)*

*Luca Cheri (Fondazione Mont'e Prama)*

*Ilaria Orri (Fondazione Mont'e Prama)*

*Anthony Muroi (Fondazione Mont'e Prama)*

#### Introduction

Subterranean environments present a unique constellation of challenges for archaeological investigation, conservation, and public communication. Their restricted visibility, architectural complexity, volumetric morphology, and often fragile material records require methodologically robust digital workflows capable of generating precise, multimodal datasets. This paper presents the integrated digital documentation of the Hypogeum of San Salvatore (Sinis Peninsula, Sardinia), carried out through a collaboration between the Fondazione Mont'e Prama and DARKLab at Lund University. The project aimed to produce high-resolution 3D digital content to support archaeological research, enable systematic monitoring, and expand accessibility. This material will be disseminated both online through the AIR platform and offline through the Fondazione's valorization and public engagement activities, including exhibitions, conferences, and other outreach initiatives.

The Hypogeum of San Salvatore is a late antique subterranean complex dating to the 4th century CE, composed of five interconnected rooms organised around a circular space with a central well. Its architecture is distinguished not only by its structural layout and centrality of water—an element traditionally linked to ritual practices—but also by a remarkable corpus of charcoal drawings executed on its walls. These drawings vary widely in mastery,

intentionality, and iconographic refinement. Some appear as part of a deliberate decorative programme, while others, more spontaneous and superimposed, are interpreted as ex-votos left by visitors. The monument's archaeological, artistic, and ritual significance is considerable, yet prior documentation relied primarily on traditional surveying and photography, which were insufficient to capture its full geometric, spatial, and graphic complexity.

#### Methods and materials

To overcome these long-standing limitations, our team implemented a high-resolution multimodal acquisition strategy that integrates Terrestrial Laser Scanning (TLS) and close-range photogrammetry in a low-light subterranean context. During fieldwork, 105 TLS scans were conducted using a FARO Phase Shift scanner, covering the entire hypogeum, its architectural surfaces, vaults, wells, and the surrounding church and external area. The TLS dataset was processed and aligned in FARO Scene, producing a georeferenced unified point cloud of approximately seven million points. This dataset served as the geometric backbone for subsequent multimodal integration.

To document the charcoal drawings at the level required for conservation monitoring and iconographic analysis, we conducted an extensive photogrammetric campaign comprising 2,034 images, averaging approximately 400 images per room. These photographs were aligned and co-registered with the TLS data in Reality Capture, ensuring that the generated models preserved both the metric accuracy of laser scanning and the richness required for detailed interpretation. The resulting room-level models integrate TLS-derived geometry with photogrammetric colour and texture. For final textures, only the IBM images were enabled to obtain the highest possible resolution. Exported models, prepared for online dissemination through the Archaeological Interactive Report (AIR) platform, were optimised at 10 million triangles per room to maximise detail while ensuring performant web-based rendering.

The digital workflow produced measurable advances in the documentation and interpretation of the Hypogeum. First, the TLS and photogrammetric models revealed architectural details that had not been previously recorded

using traditional methods. These include more precise measurements of floor levels, the depth and morphology of wells across the rooms, and subtle variations in wall curvature and surface deterioration. Such information is critical for both archaeological interpretation and the development of long-term conservation strategies. Second, the high-resolution textures of the charcoal drawings allow for a significantly improved reading of the iconography and state of preservation. Previously overlooked or barely visible elements—including faint lines, palimpsestic overlaps, and gradations of pigment—are now discernible, enabling improved classification, stylistic study, and monitoring of their progressive deterioration.

#### Results and Discussion

The project also demonstrates how carefully designed digital workflows can overcome classical obstacles of subterranean documentation, including the absence of natural light, limited space for imaging equipment, and complex geometry. The integration of TLS and photogrammetry within a coherent metric framework—supported by controlled lighting conditions—provides a replicable methodology for subterranean digital archaeology. Furthermore, the workflow ensures that 3D models are not only high quality but also semantically enriched, interoperable, and ready for reuse across multiple research and public-facing contexts.

Beyond research outcomes, the project directly supports the Fondazione Mont'e Prama's mission to promote the cultural heritage of the Sinis Peninsula through integrated archaeological, landscape, and public-engagement strategies. The 3D models have been published online through AIR, enabling researchers, students, and the general public to explore the hypogeum remotely. Users can examine the entire complex, navigate individual rooms, and visualise the charcoal drawings with their associated metadata. This is particularly important given the physical constraints of the monument: the subterranean environment is not accessible to visitors with mobility impairments, and routine public access must remain restricted due to conservation sensitivity. Through immersive virtual experiences derived from the digital

dataset, access to the site is significantly expanded without compromising its preservation.

The Hypogeum of San Salvatore demonstrates how digital tools can illuminate enclosed and historically layered contexts that resist conventional archaeological approaches. At the same time, it highlights the need for integrative frameworks that combine metric precision, visual fidelity, semantic enrichment, and multi-stakeholder collaboration. By presenting this case study, we aim to contribute to broader discussions on best practices for surveying, documenting, interpreting, and communicating subterranean archaeological sites. The project offers a replicable model for approaching complex underground environments and emphasises the importance of digital infrastructures that support both scientific inquiry and public engagement.

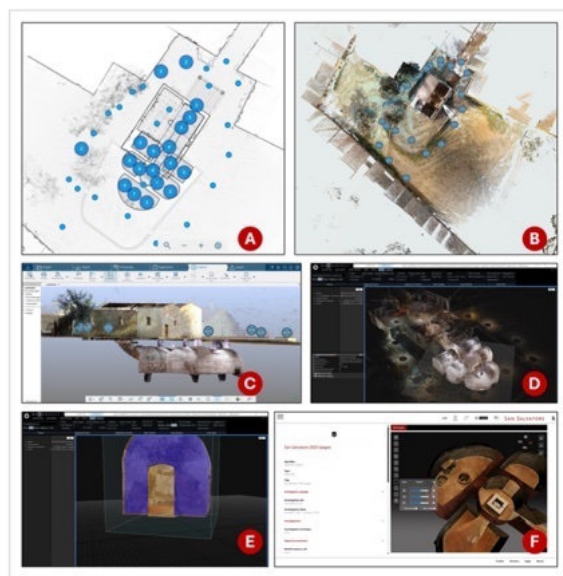


Figure 1: Digital workflow of the San Salvatore project: scans distribution in the hypogeum (A), the church, and its surrounding area (B). Scan data processing in Pure Scene (C); scans and photogrammetry combined in Reality Scan (D). Independent texturing of the rooms (E); online publication of the 3D models using the AIR platform (F).

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## 412. Mining the scape – Laserscanning the archaeological mining landscape of Hallstatt

*Matthias Kucera (University of Vienna)*

*Daniel Brandner (Natural History Museum Vienna)*

*Bernhard Groiss (Riegl LMS)*

*Bernd Paulowitz (World Heritage Salzkammergut)*

### Abstract

3D recording of cultural heritage and archaeological sites became a crucial part of documentation, archiving and analysis. The integrated application of various methods enables preservation of sites - and situations - under risk in generating digital twins. Starting from architecture, archaeological landscapes, excavations and all different types of cultural heritage, the recording of cavities is among the most challenging tasks. Most scenarios are very specific and demand multiple approaches for fast, efficient and accurate data acquisition (Zhang et al. 2024; Marini et al. 2022). Several factors can influence the decision for the best survey strategy among which are e.g. the geological and physical environment, remoteness, accessibility, availability of control points and physically challenging situations. In addition, different methods and survey strategies implement a different level of absolute and

relative accuracy and precision. Also, logistical – and financial – aspects must be taken in account.

At the prehistoric salt mines in Hallstatt/ Austria, long-term archaeological research was able to reveal aspects of the fascinating life, work and death of the mining persons. Whereas Terrestrial Laserscanning (TLS) was first introduced in 2006 for recording parts of the prehistoric mines, we want to present latest (2025) applications of Laserscanning covering and connecting areas in and around the mine. Underground data is combined with data from outside the mines gained also by TLS and airborne Laserscanning. The terrestrial sensors VZ-4000i, VZ-2000i, VZ-600i and the airborne sensor VUX-120 combined with RiLOC-F mounted on a drone came to operation. The overall aim was to showcase the recording of a complete over- and underground archaeological landscape at the current highest possible level of absolute and relative accuracy and to enable visualization of complex correlations of features above and below ground.

#### Introduction

The prehistoric salt mines of Hallstatt, located in Austria's Northern Calcareous Alps, date back to around 5000 BCE and were continuously exploited through the Bronze and Iron Ages, shaping the Hallstatt culture. The mines lie within the Haselgebirge formation, composed of Permian-age rock salt, gypsum, clay, and marl intensely folded by Alpine orogeny. This complex geology created accessible salt deposits but also unstable slopes. The steep, fractured limestone terrain, combined with groundwater flow and salt dissolution, have caused landslides and rockfalls, which endangered and destroyed the prehistoric salt mines several times. Even today, the area remains susceptible to mass movements, requiring constant geological monitoring and stabilization measures.

Whereas geodetic surveying is already difficult and very specific in stable cavities, it becomes even more challenging under such unstable conditions. Based on centuries of geodetic experience of mining engineers – the so called "Markscheider" – the accurate recording of finds and artefacts in the prehistoric mines relies on local coordinate systems valid for a specific epoch. Thus, each mine has its distinguished coordinate system, which is correlated

from time to time with geodetic coordinates outside. Due to slow mass movements in the surrounding area, constant geospatial monitoring is crucial to guarantee accurate georeferencing. It is of mayor interest to gain a 3d model of the whole archaeological landscape inside and outside the mine. This model represents consequently one specific moment in time and can be used for geometry-based alignment of measurements taken earlier and later.

#### Methods

During a two-day survey in August 2025 several sensors were applied to cover most of the prehistoric sector Christian v. Tusch-Werk, the Christina mine passing by this sector, the surrounding area of the entrance of the Christina mine itself and the landscape covering these underground structures. Because of the vegetation – the area is mostly forested – and the size of the area outdoors, an airborne sensor was chosen. The Riegl LMS VUX-120 is perfectly suited to be mounted on a drone (Acecore NOA) not exceeding the lift of weight of 25 kg regarding legal and flight operation issues. In combination with a RiLOC-F unit, geometry-based alignment of the data and refinement of the flight trajectory is achieved, while the unit is operating in RTK FIX mode (Pöpl et al. 2024).

The entrance area of the Christina mine and its tunnel leading to the Christian v. Tusch-Werk sector was scanned with terrestrial Riegl LMS VZ-2000i. Outside, the scanner was operated in RTK FIX mode to guarantee georeferenced positioning. To increase redundancy and enable geodetic control, retro targets were placed and scanned, which served as control points based on a geodetic survey. Both the airborne data and the terrestrial data were aligned according to scanned geometry (rock faces, mining buildings...). The extremely narrow tunnels excavated during the last 30 years at the Christian v. Tusch-Werk were scanned with a VZ-600i. Being light weighted, fast, ruggedized and precise, this sensor is suited perfectly for the harsh environment inside the mine. Although both terrestrial scanners can be operated in a kinematic mode – the scanner is moved while scanning – recording of static single scan positions was chosen to gain maximum accuracy. When entering



the area of Christian v. Tusch-Werk we took care to place both scanners at the same positions vice versa to record the same geometry to foster accurate alignment of the data during processing.

Finally, all datasets were combined and complemented by a dataset collected with a terrestrial long-range scanner - VZ-4000i - during a one-day visit earlier this year. The resulting pointcloud visualizes the correlation of submerged and topographical features outside the mine at a high level of absolute and relative accuracy and resolution.

#### Discussion and conclusion

With this project we wanted to showcase a specific workflow for 3D digital recording of cavities including the covering landscape. The techniques presented guarantee the highest level of intrinsic accuracy based on the involved sensors, and processing algorithms and absolute accuracy relying on geodetic surveying above ground and GNSS solutions. The dataset represents a rigid model derived from geometry-based alignment. It can serve as a geometric back bone for further 3d datasets, whether based on LS or photogrammetry. Whereas our main scientific interest focused on the methodological approach, the resulting data will be crucial for further archaeological analysis, interpretation and visualization.

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## S6: Unlocking Hidden Treasures: Digital Methods as the Key to Open Archaeological Collections for Research and Teaching

*Louise Tharandt*, Humboldt-Universität zu Berlin

*Anna Gnyp*, Humboldt-Universität zu Berlin

*Sophie Schlosser*, Ostbayerische Technische Hochschule Regensburg

**Location:** Hörsaal 02

**Session Format:** Standard

University and museum collections represent a rich and diverse array of archaeological objects, assembled over decades through research, excavations, donations and looting. These collections often contain unique and significant objects that have the potential to greatly enhance our understanding of past and recent cultures and societies (Wissenschaftsrat, 2011). However, the full research potential of these collections often remains untapped for various reasons. Besides funding, university and museum collections face a multitude of obstacles that hinder their accessibility and usability. This can make it difficult for researchers to discover and access sufficient and relevant material. The dispersal of objects across different locations can lead to the fragmentation of assemblages and the loss of contextual information. Unknown origins and bias in data limit our understanding of history. Furthermore, the lack of dedicated resources and expertise for collections management can result in inadequate preservation and documentation, further exacerbating these issues. Digital methods and tools can make a significant contribution to addressing these issues. Through the digitisation of objects or data and the use of semantic databases up to machine learning algorithms it is possible to (re)discover hidden or inaccessible data, and reunite dispersed objects across different locations and institutions. Ethical and legal aspects of collection objects can be addressed more effectively. The

potential of collection objects as teaching resources could be utilised and expanded upon.

This session aims to explore new approaches in which researchers, educators, and collection managers are leveraging university and museum collections to advance archaeological knowledge and practice. By bringing together a diverse range of perspectives and experiences, we hope to stimulate a productive dialogue on the role of university and museum collections in archaeology, enhancing their use in a way that is appropriate to their significance. We also seek to showcase creative and effective strategies for working with collections (Andraschke & Wagner, 2020). We invite contributors to share their experiences and insights on how to leverage digital methods, to unlock the hidden treasures within these collections and maximise their potential for research, teaching, and public engagement.

We welcome papers addressing (but not limited to) the following topics:

1. **Revealing Collections:** Efforts to create or enhance digital catalogues, databases, and 3D repositories to increase accessibility and preserve objects virtually. This can include discussions on the use of digital methods such as photogrammetry, laser scanning, or linked opened data and open data infrastructures (Wagner et al., 2019) to create immersive and interactive experiences with collections.
2. **Unearthing Data:** Data science methods to uncover, integrate, analyse, publish and long-term archive previously hidden, inaccessible or new data from collections. This can include open science practices, the use of advanced data mining techniques, machine learning algorithms (Brandsen et al., 2020), 3D digitisation and crowdsourcing initiatives to extract valuable information from unstructured or poorly documented datasets and to permanently archive the data.
3. **Considering Ethical Aspects and Repatriation:** Addressing the ethical dimensions of archaeological collections, including the provenance, display, and description of objects, using digital tools (Shad et al., 2024). This involves provenance research, supporting repatriation efforts (Krupa & Grimm, 2021), and fostering collaboration with descendant, Indigenous, and local communities. We particularly

welcome submissions on decolonising collection practices and co-creating knowledge through inclusive, dialogue-based approaches that honour cultural sovereignty and lived heritage.

4. **Reuniting Dispersed Collections:** Strategies to bridge gaps between objects split across different locations, institutions, or databases, re-contextualise scattered finds and recombine or reconstruct fragmented objects (Roßberger et al., 2018). This can involve collaborative efforts between universities, museums, and other cultural institutions to share data and resources (Galanakis & Nowak-Kemp, 2013).
5. **Teaching (with objects):** Case studies demonstrating how scientific collections have been employed through digital methods in archaeological research projects or as teaching tools, fostering hands-on learning and research-led teaching. This can include innovative pedagogical approaches that integrate digital or tangible collections into the curriculum (Callieri et al., 2023), as well as student-led research projects that utilise university collections.
6. **Engaging, Collaborating, Transforming:** Initiatives that connect collections with local communities, museums, and other institutions via digital means, encouraging public engagement and interdisciplinary collaboration (Wessman et al., 2019). This can include 3D visualisations, outreach programs, exhibitions, citizen science projects and public lectures that showcase the significance of university or museum collections and their relevance to contemporary issues. Contributions on how collections can be improved or expanded accordingly are equally welcome.

We encourage submissions from researchers, educators, and collection managers at all career stages. By sharing best practices, success stories, and lessons learned, we hope to inspire more effective use of university and museum collections and foster a network of scholars dedicated to their study and preservation.

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**16:00 – 16:20** 260. We have already digitized them. A Framework for Museum Collections in Research and Teaching  
*Valentina Salcedo Paparoni (Stiftung Preußischer Kulturbesitz, Staatliche Museen zu Berlin); Adriana Günzel (Institut für Archäologie und Kulturanthropologie, Abteilung für Klassische Archäologie); Matthias Lang (Bonn Center for Digital Humanities, Rheinischen-Friedrich-Wilhelms-Universität Bonn)*

**16:20 – 16:40** 143. Extending the FAIR Principles to Archaeological Objects through Persistent Identifiers and Standardized Metadata  
*Rorie Edmunds (Independent Scholar); David Novák (Institute of Archaeology of the Czech Academy of Sciences); Anthony Corns (The Discovery Programme);*

*Yiu-Kang (Gary) Hsu (Deutsches Bergbau-Museum Bochum); Thomas Rose (Deutsches Bergbau-Museum Bochum); Kieron Niven (Archaeology Data Service); Jens Klump (CSIRO & IGSN e.V.); Esther Plomp (University of Aruba); Shawn Ross (Macquarie University); Jan Sessing (Deutsches Bergbau-Museum Bochum); Christin Keller (Deutsches Archäologisches Institut)*

**16:40 – 17:00** 237. Reimagining Archaeological Repositories: Towards Digital Access and Research Visibility in Nigeria  
*Ishaq Ishaq (Ahmadu Bello University Zaria)*

**17:00 – 17:20** 137. Engaging, collaborating and transforming digital cultural heritage tools design by use of Design Science Research (DSR)  
*Martha Mosha (University of Cologne); Øyvind Eide (University of Cologne); Lorenzo Cantoni (Università della Svizzera italiana)*

**17:20 – 17:30** Break

**17:30 – 17:50** 157. On Connection: Ethical and digital approaches to ancient West Asian seals  
*Sebastian Hageneuer (Berlin-Brandenburg Academy of Sciences and Humanities); Elisa Roßberger (Freie Universität Berlin)*

**17:50 – 18:10** 152. From Excavation to Experience: Sharing the Dig Hill 80 Digital Archive through a Spatial Context  
*Sarah Tucker (Virginia Tech); Todd Ogle (Virginia Tech); Simon Verdegem (BAAC Vlaanderen)*

|                          |                                                                                                                                                                                                                                                                                                                          |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>18:10 –<br/>18:30</b> | 329. Lessons learned from early adoption: Digital recording of archaeological finds and more at the LVR-Landesmuseum in Bonn, Germany<br><i>Irmela Herzog (LVR-State Service for Archaeological Heritage)</i>                                                                                                            |
| <b>18:30 –<br/>18:50</b> | 322. Combining old school methods with new school technology: the Portuguese National Archaeology Museum case study<br><i>Miguel Almeida (Morph - Geociências); João Pimenta (Museu Nacional de Arqueologia); Luís Gomes (University of Lisbon), Vinícius Dentzien; António Carvalho (Museu Nacional de Arqueologia)</i> |
| <b>18:50 –<br/>19:10</b> | 22. Seeing into the Depths - How the 3D Scanning of Artifacts has Helped Provide a Deeper Understanding of the Submerged Lakebed Tsuzuraozaki Site in Shiga Prefecture, Japan<br><i>Corey Noxon (Ritsumeikan University); Kenichi Yano (Ritsumeikan University)</i>                                                      |
| <b>19:10 –<br/>19:30</b> | Discussion                                                                                                                                                                                                                                                                                                               |

## 22. Seeing into the Depths - How the 3D Scanning of Artifacts has Helped Provide a Deeper Understanding of the Submerged Lakebed Tsuzuraozaki Site in Shiga Prefecture, Japan

*Corey Noxon (Ritsumeikan University)*

*Kenichi Yano (Ritsumeikan University)*

In a small local museum at the north end of Lake Biwa at the center of Shiga Prefecture is a small single room display containing dozens of special artifacts from a submerged archaeological site which are rarely seen. The Tsuzuraozaki submerged lakebed site in Shiga prefecture was first recognized as an archaeological site over 100 years ago in 1924. The site was initially identified through the accumulation of largely intact pottery from the site being brought up by locals in fishing nets, with some of the pieces dating back to the Early Jomon period, approximately 7000 years ago. Investigations have been ongoing, and since 2010 there have been approximately 20 investigations utilizing robotic submersibles at the site 1,2. In 2022 a project was started to thoroughly document recovered pottery from the site which was being housed in the Tsuzuraozaki Lakebed Historic Remains Museum<sup>3</sup>. Recording methods included traditional line drawings, colorimeter readings, and using photogrammetry to create 3D models of the pottery being investigated. Not only were some of these pieces quite old, but due to their unique depositional circumstances, they also provide some additional insights into the environment in which they were resting for thousands of years. Due to the iron rich lakebed soils in Lake Biwa many of the recovered pottery pieces had lacustrine iron-rich deposits adhered to pottery surfaces where the exposed portions of the pottery met the upper surface of the lakebed. These deposits provided a unique challenge to accurately record the shape of the pottery, a task which photogrammetry was well suited to handle.

The initial recording process was completed in 2024, but 3D analysis and interpretation of those scans has continued from that point, and has yet to be formally reported on. This presentation will provide a brief explanation of how the pottery from the Tsuzuraozaki site was recorded using photogrammetry and the methods used to try to create realistic digital copies of those objects. Discussion will then cover the approaches used to measure and further visualize the often fragile lacustrine iron deposits present on much of the pottery including heatmapping vessel thickness through simple model segmentation and distance from reference mesh calculations. Another visualization approach to be discussed to better visualize how the vessels were deposited on the bottom of Lake Biwa are planar visualizations based on iron deposit positioning for the different pieces. Finally, viewing the set of these scans in their entirety, we can begin to delve into some broader insights regarding the depositional processes that were occurring 70m below the surface of Lake Biwa over the course of thousands of years.

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## 137. Engaging, collaborating and transforming digital cultural heritage tools design by use of Design Science Research (DSR)

*Martha Mosha (University of Cologne)*

*Øyvind Eide (University of Cologne)*

*Lorenzo Cantoni (Università della Svizzera italiana)*

### Context

The University of Cologne host a repository of archaeological research from Africa with data from rock art research which was conducted in Namibia from as early as 1963. The repository is available on open access and has been used extensively by other researchers over the years however access from the general public is lacking. A research project is proposed which looks into co-designing a digital heritage tool that would be used to access the data by the public (Mosha & Cantoni, 2021).

The idea behind it is such that a community in Namibia would be brought together to design a digital tool for the public so they can engage with the content within the repository. While the data is hosted in Germany, the co-design sessions would be conducted with the community within the Brandberg National Monument Area (BNMA) in Namibia which is where the rock art was recorded from. The conundrum is how to get the imagined community to design a tool around data from a repository, in Germany. One has to keep in mind that this community has a cultural heritage connection to the rock art which is found in a remote area.

The Design Science Research (DSR) paradigm was chosen to solve the problem at hand especially as there is a need to create an artifact. DSR is seen as a way to balance the needs of a researcher and community at large (Cole et al., 2005).

### Main Argument



The DSR process involves the basic design process with a number of reiterative evaluation sessions in between (Vom Brocke et al., 2020). The research argues that the DSR paradigm can be used in this cultural heritage study even though it is rooted in Information Science (IS). Over the years, DSR has been used in other fields of study in cases where there is a need to create a solution to a design problem. A use of different data collection methods afforded by the DSR paradigm would allow for a systematic approach to co-design the tool. This approach also offers a robust methodology for solving the problems that might arise during the design process.

The study, still on planning stage, proposes the use of four pre-data collection methods including; desktop research, expert interviews, project kick-off workshop, and stakeholder relationship mapping. The basic design process would include; problem definition, ideation workshop, design sprint and user testing. These will be evaluated by use of; affinity mapping, low-fidelity prototyping, heuristic evaluation, stakeholder interviews, stakeholder engagement and expert evaluations. All the above would culminate into a seminar as part of the post co-design session. All the mentioned would undergo monitoring and evaluations from the researcher at different levels to gauge if the process is working.

#### Application

The results of the project in designing a public digital cultural heritage tool using DSR would add to the fields of study that makes use of the paradigm. Regardless of the project's empirical success, the results will advance the understanding of the DSR paradigm and its use in similar cultural heritage studies.

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### 143. Extending the FAIR Principles to Archaeological Objects through Persistent Identifiers and Standardized Metadata

*Rorie Edmunds (Independent Scholar)*

*David Novák (Institute of Archaeology of the Czech Academy of Sciences)*

*Anthony Corns (The Discovery Programme)*

*Yiu-Kang (Gary) Hsu (Deutsches Bergbau-Museum Bochum)*

*Thomas Rose (Deutsches Bergbau-Museum Bochum)*

*Kieron Niven (Archaeology Data Service)*

*Jens Klump (CSIRO & IGSN e.V.)*

*Esther Plomp (University of Aruba)*

*Shawn Ross (Macquarie University)*

*Jan Sessing (Deutsches Bergbau-Museum Bochum)*

*Christin Keller (Deutsches Archäologisches Institut)*

The FAIR Principles—Findable, Accessible, Interoperable, and Reusable—are central to Open Science and the transparency of research (Wilkinson et al. 2016). Persistent Identifiers (PIDs) such as Digital Object Identifiers (DOIs) are essential to operationalizing these Principles by creating stable, machine-

actionable links between resources and their metadata. While the use of PIDs for some outputs and entities (e.g., datasets) is beginning to be established within Archaeology, they are rarely applied to archaeological objects—the physical materials/samples that underpin archaeological research.

Across archaeological laboratories and repositories, objects are often catalogued with local, non-persistent codes recorded in spreadsheets or database tables. The use of such local identifiers offers limited exposure and a lack of interoperability, making it difficult to discover archaeological objects and to connect them with related research outputs and entities (analytical results, publications, etc.). This situation limits reproducibility and long-term reuse.

This presentation introduces a community-driven framework for applying the International Generic Sample Number (IGSN ID; <https://support.datacite.org/docs/igsn-ids>) to archaeological objects, together with a discipline-specific metadata profile developed by the IGSN–DataCite Archaeology and Cultural Heritage Community of Practice (Archaeology CoP; <https://ev.igsn.org/communities/archaeology>). The aim is to make archaeological objects FAIR by assigning them PIDs and describing them using standardized metadata that supports discovery, citation, and reuse.

Two guiding questions frame this work:

1. How can IGSN IDs be effectively integrated into archaeological workflows?
2. What metadata structure best supports the management and interoperability of archaeological objects?

The IGSN ID is a globally unique identifier for material samples, initially developed for the Geosciences and now maintained through a partnership between IGSN e.V. and DataCite (Buys & Lehnert 2021). Each IGSN ID resolves to a landing page that presents rich, descriptive information, ensuring that the sample registered with the IGSN ID remains discoverable and citable

even if its physical state or location changes. IGSN IDs are technically DOIs and use the DataCite Metadata Schema (<https://schema.datacite.org/>) for registration. This enables seamless integration with other components of research data infrastructure, such as ORCID iDs (for people; <https://orcid.org/>) and Research Organization Registry IDs (for institutions; <https://ror.org/>).

Because IGSN IDs are DOIs, their assignment can fit easily into existing cataloguing systems. Each identifier comprises a prefix and suffix, enabling institutions to preserve local label structures while ensuring global uniqueness. Objects can carry their identifiers as QR codes or barcodes linked to their landing pages. These machine-readable labels streamline inventory management and reduce reliance on isolated spreadsheets. Hierarchical relationships among objects can also be expressed in the metadata, enhancing provenance tracking.

The Archaeology CoP was established to adapt the IGSN ID framework to archaeological needs. Using an iterative, participatory approach, the CoP:

- Compiled object-level metadata from diverse archaeological subfields to draft an initial metadata profile.
- Refined the profile by testing it against real archaeological objects and comparison with existing schemata and vocabularies.
- Crosswalked its elements to the DataCite schema to ensure technical compatibility.

The resulting Archaeological Sample Metadata Profile (<https://doi.org/10.5281/zenodo.17254975>) and Crosswalk Recommendation (<https://doi.org/10.5281/zenodo.17446558>) are publicly available for the Archaeology community to utilize. The Metadata Profile defines 22 core metadata properties, grouped as follows: investigation context; actors; discovery metadata; collection details; sample characterization; and relations. Profile elements are mapped directly to the DataCite Metadata Schema within the Crosswalk Recommendation. The Profile also recommends the use of controlled vocabularies such as the Getty AAT

(<https://www.getty.edu/research/tools/vocabularies/aat/>) and the FISH Terminologies (<https://heritage-standards.org.uk/fish-vocabularies/>) to promote semantic interoperability.

The integration of IGSN IDs into archaeological workflows delivers several benefits: FAIR compliance, alignment with the CARE Principles (Collective benefit, Authority to control, Responsibility, and Ethics; Carroll et al. 2020), interoperability with other PID systems, and sustainability through the DataCite infrastructure. Together, these benefits transform archaeological objects into accessible and reusable research assets rather than isolated artefacts.

The CoP's outputs are conceived as living standards, governed through IGSN e.V. and sustained by community input. There is also the potential to extend the Profile to archaeological subdomains or for development of complementary metadata profiles such as for archaeological sites. The long-term vision is a consistent, global system in which all archaeological objects are registered with persistent identifiers and described by interoperable metadata.

Assigning IGSN IDs and adopting a standardized metadata profile increases the FAIRness of physical objects resulting from archaeological research. By embedding PIDs into institutional workflows and aligning metadata practices with international standards, Archaeology can ensure that its core research materials are discoverable, citable, and reusable—fully integrated within the digital ecosystem of Open Science.

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## 152. From Excavation to Experience: Sharing the Dig Hill 80 Digital Archive through a Spatial Context

*Sarah Tucker (Virginia Tech)*

*Todd Ogle (Virginia Tech)*

*Simon Verdegem (BAAC Vlaanderen)*

### Context

The Dig Hill 80 project documents a significant World War I excavation in Wijtschate, Belgium. During this project, archaeologists discovered trench systems, dugouts, and human remains. Although the physical site is no longer accessible, the digital record of the excavation provides new opportunities for open access, interpretation, and storytelling. This paper presents the workflow, curation process, and outreach rationale behind the creation of a web-based 3D experience of Dig Hill 80, developed using 3DVista. The design process involved close collaboration among the archaeological team, digital artists, and developers, striking a balance between accuracy and usability. The project's goal was to translate excavation data into an engaging, publicly accessible online exhibition that also retains scholarly value.

The resulting platform allows users to navigate a full 3D model of the excavation, selecting "points of interest" that reveal embedded 360° video commentary by the lead archaeologist and interactive 3D models of key finds. The research question driving this work asks: How can complex archaeological data be effectively optimized, curated, and narrated for open, web-based dissemination without compromising research integrity or accessibility?

### Main Argument

This paper argues that the Dig Hill 80 3DVista project demonstrates a tension between scientific transparency and narrative design in digital reproductions. By translating excavation data into an interactive, web-based environment, the project shifts digital archaeology from documentation toward experiential storytelling. The argument is that the workflow decisions (what data to include, how to optimize models, where to embed narrative commentary) are not only technical but rather interpretive acts.

The project combined multiple data types, including high-resolution orthophotos, photogrammetric meshes, structured-light scans of finds, and 360 videos (Figure 1). These assets were curated and integrated into points of interest that enable users to explore the site interactively and engage with contextualized narratives. Decisions such as data compression, mesh optimization, format conversion (.glb), and platform choice (3D Vista over Potree or Mozilla Hubs) balanced trade-offs between fidelity, accessibility, and narrative clarity, illustrating that technical workflow is closely linked to curatorial and interpretive practice.

#### Applications or Implications

This work has several wider implications for computer applications and quantitative methods in archaeology:

**Curatorial Storytelling:** Digital interfaces designed by public humanists play a crucial role in shaping archaeological narratives. Recognizing this curatorial intervention enables the design to be informed by theory.

**Web Optimization:** It is important to acknowledge that manipulation, even in the service of Web accessibility, has an impact on the story that the material tells. At the same time, optimization for the Web typically works antagonistically with preservation practice.

**Public and Scholarly Impact:** Web-based 3D environments can simultaneously serve as tools for researchers and academics, as well as educational and engagement tools for the public (Mayfield & Simmons, 2018), based on the level of engagement and the metadata accompanying the 3D assets.

**Ethics and Accessibility:** Digital heritage, particularly involving human remains and warfare, raises important questions about responsible representation and preservation. Decisions about creating public content must be made thoughtfully, as they reflect our professional ethical responsibilities.

**Accessibility:** Creating immersive heritage spaces for the web ensures that a larger audience has access to the information while adhering to digital preservation standards.

The Dig Hill 80 3DVista online experience demonstrates how archaeological projects can integrate technical innovation with interpretive storytelling. Through a structured workflow of data optimization, curatorial selection, and narrative integration, the project transforms excavation documentation into a publicly accessible digital environment that can be experienced as “... thinking apparatuses, meeting spaces for diverse audiences, ...” Perry, 2018, p.217).

This work provides practical insights for translating complex archaeological datasets into web-based experiences. By emphasizing both scientific rigor and narrative clarity, these approaches can strengthen engagement between archaeologists, cult

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## 157. On Connection: Ethical and digital approaches to ancient West Asian seals

*Sebastian Hageneuer (Berlin-Brandenburg Academy of Sciences and Humanities)*

*Elisa Roßberger (Freie Universität Berlin)*

University and museum collections worldwide hold vast repositories of archaeological artefacts, amassed over decades through excavations, research, donations and acquisitions. Among these objects, ancient West Asian seals, sealings and sealed clay tablets (c. 6,500–100 BCE) constitute one of the richest yet most fragmented bodies of artefacts that once circulated as instruments of trust, identity, and authority. Seals provide valuable insights into administrative systems, visual culture and social structures of ancient West Asian societies through artistically engraved visual and textual elements composing scenes and texts of rich information. Many of these objects are dispersed across multiple institutions in West Asia and beyond, and while much of this material has been published, it remains difficult to access or integrate into a coherent overview.

In response to this situation, the KIŠIB Project ('Digital Corpus of Ancient West Asian Seals and Sealings'), housed at the Berlin-Brandenburg Academy of Sciences and Humanities (BBAW), the Ludwig-Maximilians-University Munich (LMU) as well as the Bavarian Academy of Sciences and Humanities (BAdW), was established. The project is developing a distributed, semantically enriched digital infrastructure with the aim of virtually reuniting over 80,000 seals, sealings and sealed clay tablets that have been documented in various publications and are held in university and museum collections. Drawing upon previous projects such as ACAWAI-CS and DigANES (Roßberger 2024; Roßberger and Kurmangaliev 2023; Roßberger 2022), the KIŠIB project combines archaeological research, computer science and heritage ethics to maximise the research potential of these objects, which are dispersed across the globe.

KIŠIB's central argument is that reconnecting dispersed archaeological collections requires an integrated digital and ethical framework that combines semantic technologies with equitable collaboration. The project's core contribution lies in the technical implementation of FAIR data and the integration of CARE principles (Collective Benefit, Authority to Control, Responsibility and Ethics), ensuring digital accessibility goes hand in hand with ethical responsibility. By combining computational precision with humanistic reflection, KIŠIB reimagines the digital catalogue as a relational, dialogical corpus that reconnects artefacts to their ancient and modern histories of acquisition and research.

The methodological and infrastructural strategies developed by KIŠIB are directly relevant to the objectives of this CAA session, particularly with regard to the topics of 'Revealing Collections', 'Unearthing Data' and 'Teaching'.

1. **Revealing Collections:** KIŠIB demonstrates how semantic web technologies can reveal connections between objects from different collections. By connecting datasets through Linked Open Data, the project makes thousands of seals discoverable across institutional boundaries. The integration of standardised vocabularies enables users to explore collections by iconographic motif, text elements or archaeological provenance, creating new avenues for research for scholars and the general public alike.

2. **Unearthing Data:** This project provides the computational infrastructure needed to analyse large-scale collections of seals and seal impressions. Image-based annotation pipelines and semantic modelling make it possible to compare collections that were previously impossible to bring together. This paves the way for quantitative approaches, such as similarity detection, motif clustering and network analysis, which can identify stylistic traditions or administrative patterns across time and space.

3. **Teaching:** Beyond scholarly research, KIŠIB develops open, multilingual interfaces that provide students and educators with access to the corpus. These resources show how digital infrastructure can enrich teaching with archaeological collections and promote public awareness of ancient West Asian heritage within a global context.

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## 237. Reimagining Archaeological Repositories: Towards Digital Access and Research Visibility in Nigeria

*Ishaq Ishaq (Ahmadu Bello University Zaria)*

Archaeological collections in Nigerian museums embody centuries of cultural evolution, technological advancement, and social transformation. Yet, despite their scholarly value and relevance to global heritage discourse, these collections remain largely invisible within the research and teaching landscape. The absence of adequate documentation, poor storage infrastructure, and limited digital access have collectively obscured their potential for

academic use and public engagement. This paper, drawn from empirical fieldwork conducted across four key National Museums; The National Museum Jos (NMJ), National Museum Kaduna (NMK), Nok Culture Research Station Janjala (NCRSJ), and the University Museum of Ahmadu Bello University, Zaria (UMABUZ) seeks to reimagine archaeological repositories in Nigeria through the lens of digital transformation. It proposes a framework for integrating digital methods into archaeological collection management to unlock accessibility, visibility, and research potential.

Field investigations reveal that Nigerian museum repositories are characterized by acute infrastructural decay, inadequate environmental controls, and obsolete storage systems. Storage areas are often poorly ventilated and exposed to fluctuating temperature and humidity levels that threaten the preservation of artifacts. Beyond the physical conditions, the research found that documentation systems remain highly inconsistent. Most repositories still rely on handwritten registers and card catalogues introduced in the mid-twentieth century. These manual systems are fragmented, incomplete, and vulnerable to deterioration or loss. In some museums, particularly the National Museum Kaduna and the University Museum Zaria, large numbers of artifacts sometimes exceeding several thousand items are either undocumented or partially recorded. This lack of accurate and retrievable data significantly limits both curatorial oversight and scholarly engagement.

The result is a "double invisibility": first, the physical inaccessibility of collections stored in congested and deteriorating spaces; and second, the epistemic invisibility created by the absence of digital documentation, which prevents researchers, educators, and the public from knowing what exists within museum storages. Consequently, Nigerian archaeological repositories have become what might be termed "hidden archives" or sites of immense historical and research value that remain largely unknown and underutilized. In today's digital era, such invisibility represents not merely a technical shortcoming but a profound epistemological barrier that restricts Nigeria's contribution to regional and global archaeological scholarship.

To address these challenges, this paper argues for the adoption of digital collection management systems as a transformative tool for reimagining the



future of archaeological repositories in Nigeria. Digital methods including 3D scanning, digital photography, online cataloguing, and database integration can radically expand the accessibility and interpretive potential of archaeological collections. When systematically applied, these methods can create a centralized digital archive that transcends the physical boundaries of storage rooms. Such an archive would facilitate remote research, enhance teaching materials for universities, and promote collaborative scholarship both within and beyond Nigeria.

The study highlights several interrelated dimensions of this digital transformation:

1. **Documentation and Inventory:** A standardized, digital inventory system is essential for identifying, classifying, and tracking collections. Software such as CollectiveAccess, MuseumPlus, or open-source alternatives like TMS or Omeka could be adapted.
  2. **Preservation and Conservation:** Digital documentation provides an additional layer of conservation by minimizing the need for physical handling of artifacts. High-resolution imaging and 3D models allow scholars to conduct morphological analyses and comparative studies without endangering fragile objects.
  3. **Research and Pedagogy:** Digitized collections can revolutionize teaching and research in archaeology and heritage studies. At Ahmadu Bello University, for instance, where students rely heavily on textual resources, access to digital replicas of artifacts would enable object-based learning and independent research.
  4. **Networking and Collaboration:** Digital access allows Nigerian museums to join transnational digital heritage platforms such as AfricaMuseum Digital, Global Digital Museum, or the British Museum's African collections portal.
  5. **Community Engagement and Public Interpretation:** Through digitization, museums can reconnect local communities with their cultural heritage. Digital storytelling platforms, mobile applications, and interactive exhibits can make archaeological information accessible in indigenous languages.
- While the potential of digitization is immense, the study recognizes practical and ethical challenges. These include inadequate funding, limited technical

expertise, unstable power supply, and the absence of institutional policies on digital heritage management.

The envisioned transformation requires an integrated model where physical preservation and digital access co-exist as complementary strategies. Under such a model, digitization becomes an integral part of archaeological practice. From field excavation to post-excavation curation, ensuring that every artifact recovered, documented, and stored can contribute meaningfully to research and education. Nigerian museums and university collections can thus reposition themselves as centers of innovation, scholarship, and cultural diplomacy in the digital age.

In conclusion, the paper advocates for a phased, collaborative approach involving the National Commission for Museums and Monuments (NCMM), universities, and international partners. Pilot digitization projects, starting with select repositories such as NMJ and UMABUZ, can serve as proof of concept for broader national implementation. Through training, policy reform, and sustained investment in digital infrastructure, Nigeria can move from custodial stagnation to participatory digital engagement.

## 260. We have already digitized them. A Framework for Museum Collections in Research and Teaching

*Valentina Salcedo Paparoni (Stiftung Preußischer Kulturbesitz, Staatliche Museen zu Berlin)*

*Adriana Günzel (Institut für Archäologie und Kulturanthropologie, Abteilung für Klassische Archäologie)*

*Matthias Lang (Bonn Center for Digital Humanities, Rheinischen-Friedrich-Wilhelms-Universität Bonn)*

### The Lifecycle of the Digital Object

In the digital transformation of heritage institutions, the documentation of digital copies emerges as a critical factor for both sustainability and scholarly reuse. To sustainably unlock the scholarly and pedagogical potential of digital

heritage data collections, a comprehensive framework is required that considers the entire lifecycle of a digital object, from its creation in the museum to its application in academic settings. This presentation outlines a conceptual model designed to align the institutional needs for preservation and access with the scholarly requirements for authentic data and innovative teaching tools. This approach treats digital objects not as static representations but as dynamic, reusable assets, thereby ensuring their long-term value and utility for the academic community.

#### Part I. Less is More: Creating Authentic and Sustainable Digital Assets

The foundation of this framework is the creation of authentic and sustainable digital assets. Digitization is not a neutral act of replication but an interpretive process. Digital heritage data are inherently fragile—subject to obsolescence of formats, platforms, and infrastructures. What renders them sustainable is not the technology of their capture but the robustness of their documentation. The objective must be to produce a trustworthy digital surrogate that captures not only the geometry and color of an artifact but also its material qualities and object biographies. To this end, the "digital authenticity profile" serves as a key methodological tool. It is a documented set of criteria, established through a collaborative negotiation between curators and technical specialists, that defines which essential features of an object are to be digitally recorded.

For these assets to have long-term institutional value, they must be sustainable. This requires the implementation of standardized metadata and careful documentation for scientific traceability. To fully anchor the digital object within its scholarly context, this metadata must connect to authoritative resources like the Heidelberg Accession Index, providing transparent and traceable information on provenance. Crucially, this framework advocates for a pragmatic balance. While documentation is vital, the goal is to avoid excessively complex metadata schemas that often remain purely academic exercises with little impact on actual museum practice. The guiding principle is pragmatic minimalism: essential, well-structured metadata that supports reuse without imposing excessive burdens on institutions. The documentation

must ensure scientific traceability, clarify the scope of digitization, and specify data provenance. Finally, the high-resolution master files must be stored in permanent, institutional research data repositories to ensure their preservation.

#### Part II. From Repository to Share: Digital Heritage Data as a Resource

The research data repository functions not as an endpoint but as a central hub from which a variety of products can be derived. A collaboration between the Collection of Classical Antiquities of the Berlin State Museums and the University of Bonn serves as a practical exemplar of this framework. The project's goal was to digitize the museum's collection of Greek Funerary Reliefs for teaching purposes at the university. This initiative provided a testbed for the "digital authenticity profile," requiring a complex negotiation to define an "authentic" digital representation of these marble objects and to link each model to its provenance data. The resulting high-quality, openly licensed digital surrogates were then archived in the Bonndata repository. Such high-fidelity assets form the necessary foundation for advanced pedagogical tools. While this data is used in various teaching formats, it could also be integrated into immersive applications like Virtual Reality (VR). VR is a particularly powerful educational tool as it overcomes the limitations of traditional study trips by providing a true-to-scale, interactive experience.

#### Part III. Document Once, Reuse Forever: Beyond the Single Application

While powerful, specific applications like VR face the challenge of rapid technological change and can quickly become obsolete. Therefore, the most effective strategy for ensuring long-term sustainability is not to focus on preserving a single application but to preserve the underlying data assets within the repository. By storing the well documented, high-quality models in standardized and open formats, we ensure that the data remains independent of any one technology ([https://bonndata.uni-bonn.de/dataverse/altles\\_museum\\_berlin](https://bonndata.uni-bonn.de/dataverse/altles_museum_berlin)). This approach guarantees that the significant investment in digitization retains its value over the long term, making the assets available for integration into future technologies.

In conclusion, by adopting this lifecycle approach—from the collaborative creation of authentic, traceable data, as exemplified by the Greek reliefs project, to its preservation for diverse applications—we can effectively transform museum collections. They become dynamic and sustainable resources, truly unlocked for research and teaching for generations to come.

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## 322. Combining old school methods with new school technology: the Portuguese National Archaeology Museum case study

*Miguel Almeida (Morph - Geociências)*

*João Pimenta (Museu Nacional de Arqueologia)*

*Luís Gomes (University of Lisbon)*

*Vinícius Dentzien*

*António Carvalho (Museu Nacional de Arqueologia)*

The Portuguese National Archaeology Museum occupies the Mosteiro dos Jerónimos, a major national monument originally founded by King Dom Manuel I in the early 16th century. After a long, complicated construction

history, that continued after the monarch’s death, the building underwent a series of diverse ecclesiastical, administrative, military, and commercial uses, as well as architectural changes, and inevitable decay. In 1878, during extensive renovation works, the building’s new central tower collapsed before completion. For decades, and amidst continued social unrest and protracted technical and political disputes, several reconstruction projects succeeded one another — none fully implemented. Meanwhile, the still standing western wing became the house of the Portuguese Ethnological Museum, predecessor to nowadays’ Museu Nacional de Arqueologia, with successive structural and architectural changes continuing throughout the years and eventually culminating in the current form by 1940.

In 2024, the Museum’s new renovation project — bearing direct physical impact on the building and underlying stratigraphic layers yielding significant archaeological potential — called for a thorough preventive Archaeology program. A proactive, rather than reactive, approach to archaeological mitigation was then designed, based on multi-sensor 3d modelling (combining terrestrial laser scanning, low-altitude photogrammetry and satellite imagery), extensive geophysical surveying, geotechnical coring, archaeological intrusive tests and excavations, and Building’s Archaeology. As a result of this multidisciplinary field approach, a considerable amount of new hard data concerning the building’s evolution since its 1878 debacle was produced. However, a persistent inquiry of coeval historical documents was needed to provide substantial context to the interpretation of the new physical evidence recovered from the building’s walls and underlaying archaeological record. And with exceptional correlation: if the massive 4m deep foundation occupying the whole area of the collapsed tower clearly materializes the solution proposed by the first engineering commission (in 1880), the subsequent archaeological and architectural features observed in the field clearly mirror and densify much of the events described in the historical documentation.

In retrospective, if the technology-based multidisciplinary fieldwork produced invaluable new information, it was the close combination of those technologies with traditional research methods that shed new light into the

building's history, that of Portuguese Engineering, the city of Lisbon, and the Portuguese socio-political environment in the 19th and early 20th centuries. The Museu Nacional de Arqueologia preventive Archaeology project thus serves as a significant case study of the potential of new multidisciplinary fieldwork methods, emerging from the ground of innovative commercial Archaeology projects, based on the daily interaction between archaeologists and new technologies / digital tools to develop robust diagnostic and recording procedures, field-proved in efficiency-driven real-world production environments.

### 329. Lessons learned from early adoption: Digital recording of archaeological finds and more at the LVR-Landesmuseum in Bonn, Germany

*Irmela Herzog (LVR-State Service for Archaeological Heritage)*

#### Introduction

The LVR-Landesmuseum in Bonn, Germany, has a long tradition of collecting mainly archaeological finds. In the early days, newly acquired objects were recorded in handwritten inventory books. A contribution to a publication celebrating the 150<sup>th</sup> anniversary of the museum collections in 1971 points out that, that searching for a specific fibula type required checking all the inventory books entry by entry, and that electronic data processing is the only solution (Petrikovits 1971). Digitisation began in 1974 with the transcription of the inventory books into text files. In the 1990s, a relational Paradox database was set up. Around the year 2000, additional offline databases were created in preparation for the relocation to a new storage facility. In 2000, a working group comprising members of various museums and cultural heritage institutions belonging to the Landschaftsverband Rheinland (LVR – the Rhineland Regional Council) was established. The group's task was to select common software for managing the institutions' collections. The group created a catalogue listing 18 required and 19 desired features or functions of

the software. For example, three catalogue entries refer to thesaurus functionality. The group selected a software product, an updated version of which is still used to manage over 308,000 records describing museum objects in the Landesmuseum's collection. On average, 384 new finds arrive at the Landesmuseum each working day, which need to be catalogued and physically stored according to their requirements. Since 2014, replacing the museum software has been on the agenda of the LVR department responsible for managing the digitisation and IT of the cultural heritage institutions. The department has selected a new web-based visually appealing software that incorporates many state-of-the-art features. These include LIDO support, data structures for documenting events, and integration of an open (CC BY 4.0) vocabulary for cultural objects called *Wortnetz Kultur* (Granderath & Schenk 2025).

#### Lessons learnt

The kick-off meeting for the project that aimed to migrate the Landesmuseum database to the new software took place in June 2021. Testing the functionality of the new software and preparing for the migration had a sobering effect on the future users. Several key functions listed in the 2000 feature catalogue were absent from the new software, as were features that had previously been taken for granted. For managing the museum objects and entering new data, many of these missing features are more important than the modern, highly advertised ones. These include the ability to copy selected field entries from a previously entered record, search for identifier intervals (e.g. 2024.1,0-1 to 2024.100,1-1), highlight the search terms in the data record, search for empty fields regardless of field type (e.g. object images), support the assignment of unique museum object identifiers consisting of several components, achieved by computing the next available component number, and many more. For instance, no field is provided for recording the date a photograph was taken, which could help identify damage to objects photographed repeatedly over the past 100 years. Due to word count restrictions, it is not possible to describe all of the missing features in detail.

However, the main lesson learnt is that conforming to standards does not guarantee everything is OK. For instance, the CIDOC Documentation Standards Working Group (2012) requires that “each object must be assigned a unique number or identifier, which should be recorded within the documentation system”. This is neither feasible nor appropriate for an archaeological museum with limited resources.

Controlled vocabulary and LIDO do not guarantee that search results will be as expected. Typically, an audience interested in archaeology is searching for the three basic units of information: what, where, and when.

What: This search is supported by a thesaurus, i.e. a branch of the high-standard controlled vocabulary *Wortnetz Kultur* (WNK). However, some terms used in the Landesmuseum’s thesaurus are not accepted by the WNK board (e.g. terms with a slash such as “bracelet/anklet”, but it is often difficult to determine whether the object was intended for the arm or the leg). Therefore, migrating the Landesmuseum database requires replacing several specific terms with more general ones. The WNK board also makes changes, e.g. changing the preferred term or qualifiers). Consequently, a find list ready for import yesterday could be problematic today. Sometimes, the definition of a WNK term does not account for changes in usage over time. For example, the German term “Topf” is now used for a metal cooking pot, whereas prehistorians use it for pottery. The WNK definition of “Topf” (with the qualifier “vessel”) refers to pottery. This has resulted in erroneous entries in some LVR databases.

Where: Due to legislation restricting the publication of find spots in the Rhineland following frequent looting, it is no longer possible to publish the location of archaeological sites. Therefore, any future linked open data repository of the Landesmuseum collection must not display the site coordinates, thereby restricting the “where” search and the usability of the repository.

When: The event-based structure of LIDO complicates searches for objects manufactured within a specific time interval. This can be illustrated with an example from the LVR showcase website about everyday life in the 20th century (<https://alltagskulturen.lvr.de/de/>): A devotional image printed in 1913

is found when the advanced search is used with the following search conditions:

date\_begin = 1930 and date\_end = 1950 and event = “production”

This happens because the “use” event for this object is also dated (20<sup>th</sup> century). The simplest way to avoid this issue is to use a separate field to store the production date, rather than including it in the event data structure. The NFDI4Objects working group employs this simple approach in their design of a data structure for the exchange of data on cultural heritage objects in Germany.

In conclusion, meeting museum documentation standards does not guarantee easy collection management or avoid unexpected search results. Changing the software will not increase data quality. Supporting a controlled vocabulary may even result in a loss of precision. The hopes of the Landesmuseum director from 1971 have only been partly realised. It is still impossible to locate all fibulae of a specific type hidden in the storerooms. However, we now know the location of 3032 fibulae, and the 127 objects for which the description text includes the word “Vogelfibel” (i.e. bird fibula).

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## S8: Digital Methods in Rock Art Research II. Connecting People: Reconstructing the Contexts of Past Visual Communication Systems

*Ashely Green, University of Gothenburg*

*Rebecca Döhl, University Münster*

*Eymard Fäder, University of Cologne*

*Paolo Medici, Centro Camuno di Studi Preistorici*

*Oliver Vogels, University of Cologne*

**Location:** Hörsaal BIG

**Session Format:** Standard

This year we are expanding the session's focus to the digital explorations of the creation, perception, and social circumstances of production and consumption of rock art and related visual communication systems.

The context for the formation and use of visual communication systems, such as rock art (including petroglyphs and paintings), wall art, or graffiti, is mainly analysed through formal methods of interpretation (Taçon and Chipindale, 1998). During the last decade these formal methods shifted more to digital and computational methods, comprising a wide range of approaches, applications, and techniques (Carrero-Pazos et al., 2022; Valdez-Tullett and Figueiredo Persson, 2023). These methods cover well-established GIS-centred analysis of the spatial context of rock art, computational analysis (including AI approaches) of rock art production, and extended reality (XR) applications for cultural heritage and engagement. On both the local- and large-scale, digital and computational methods play an important role in understanding visual communication systems and the people that created them. To highlight the people behind the visual communication, this session aims to explore all aspects of social engagement with rock art from its creation to its consumption and the feedbacks within these processes. While we refer

to rock art as a prime example of visual communication, we embrace all expressions of semantic visuality, such as graffiti, visual marking systems, wall art etc. We welcome contributions on methods, new insights and results from digital methods, and dissemination around the **human-centred lifecycle of rock art**:

**Creation** – Digital methods can highlight the underlying concepts, formal as ideational, and techniques used to establish certain motifs and topics and their application on the canvas. For example, digital analysis of techniques employed for shaping the figures (Díaz-Guardamino, 2023) and the analysis of panel composition, style, and chronology (Riris and Oliver, 2019).

**Position** – The spatial and socio-economic context of visual communication production provides another aspect of exploration which allows for digital methods. From studies of the placement of rock art in the landscape (Barnett et al., 2024; Döhl, 2019; Vogels et al., 2021) to the role that natural features played in the creation of rock art (Horn et al., 2023), digital methods play an important role in the multi-scalar analysis of art. Similarly, the interplay between graffiti and their application on built environments and trees are explored with digital methods.

**Perception** – Understanding perceptions in visual communication systems builds another immanent connection to the people who used the art. Visual perception and analysis using digital methods, such as eye-tracking, can help further understanding of systems and societies who created them (Silva-Gago et al., 2025). Archaeoacoustics (Díaz-Andreu and Mattioli, 2016; Rainio et al., 2025; Santos da Rosa et al., 2023) with sound propagation and soundscape measurement have also showed a great potential for exploring the perception and social role of rock art.

**Consumption** – The consumption of rock art and other visual systems might be explored both in its original context and in its modern form. The mediation and presentation of rock art and its (original) context to a modern audience, in cultural heritage projects or museums, relies heavily on digital methods (Jalandoni, 2025). Interactive web-based platforms (Green et al., 2024), direct enhanced access like XR applications (Urcia et al., 2022; Westin et al., 2021), or reconstruction of caves (Lascaux, Chauvet) based on digital 3D-



models (Geneste, 2009), for example, offer accessible ways for researchers and the public to consume rock art.

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**10:30 – 10:50** 97. A multi-tool digital approach to the analysis of rock art and metallurgical symbolism in the Arabian deserts  
*Jerome Kahl (University of Vienna)*

**10:50 – 11:10** 181. Written on the Landscape: A Quantitative Analysis of Competing Territorial and Mobile Strategies at Ḥimā  
*Giacomo Fontana (Texas Tech University); Alessia Priolella (CNRS, UMR 8167 - Orient & Méditerranée)*

**11:10 – 11:30** 106. If these walls could talk. Exploring the potential of multivariate statistics to investigate Egyptian Old Kingdom elite tomb iconography.  
*Christel Birkmann-Little (Leiden University)*

**11:30 – 11:50** 163. Using rock art and Species Distribution Models to understand climate change in Predynastic Egypt  
*Sebastián Maydana (University of Liverpool)*

**11:50 – 12:10** 372. Secular, totemic, shamanistic? – Testing rock art contexts with ABM and GIS  
*Rebecca Döhl (University Münster)*

**12:10 – 12:30** 287. Hunting arts: informing the spatial organisation of prehistoric rock art through indigenous knowledge  
*Oliver Vogels (University of Cologne)*

**12:30 – 13:30** Lunch break

**13:30 – 13:50** 244. Rock, Paper, Mesh: Integrated Approaches to Recording Desert Rock Art  
*Emma Beckett (UWA)*

**13:50 – 14:10** 220. Desert to the Sea: Reconnecting Visual Communication Systems across the Western Desert  
*Jo McDonald (CRAR+M UWA)*

**14:10 – 14:30** 56. Innovating Heritage: Digital Archaeology as a Tool for Indigenous Rock Art Engagement  
*Andrea Jalandoni (Griffith University)*

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|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:30 – 14:50</b> | 119. Visualization of bas-reliefs from three-dimensional objects – example of ornaments on the heads of moai kavakava – wooden figurines from Easter Island<br><i>Rafal Wieczorek (Uniwersytet Warszawski); Paul Horley (Cimav Campus)</i>      |
| <b>14:50 – 15:10</b> | 123. Stirring the hornet's nest: demonstrating the ritual dimensions of Northwestern Amazonian petroglyphs through geometric morphometrics<br><i>Samir Chavarro-Belafonte (University of Tübingen)</i>                                          |
| <b>15:10 – 15:30</b> | 44. Rock Solid Replicas: The Application of 3D filament Painting Technique on Pictographs in Southern Alberta, Canada.<br><i>Mavis Chan (University of Calgary); Peter Dawson (University of Calgary)</i>                                       |
| <b>15:30 – 16:00</b> | Coffee break                                                                                                                                                                                                                                    |
| <b>16:00 – 16:20</b> | 150. Imprints of Time: Reconstructing Prehistoric Expressions Through Digital Lenses<br><i>Ankita (Banaras Hindu University)</i>                                                                                                                |
| <b>16:20 – 16:40</b> | 212. A Spatial Life: Rock Art Distribution and Visibility among Mobile-pastoral Societies in the Mongolian Altai<br><i>Michael Fisher (Max Planck Institute of Geoanthropology); Dovydas Jurkenas (Max Planck Institute of Geoanthropology)</i> |
| <b>16:40 – 17:00</b> | 64. Quantifying Image Decorrelation Techniques for Rock Art: Systematic Comparison at La Pileta Cave (Málaga, Spain)                                                                                                                            |

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|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                      | <i>Rubén Parrilla (ICArEHB); María Simón-Vallejo (Universidad de Sevilla); Miguel Cortés-Sánchez (Universidad de Sevilla)</i>                                                                                                                                                                                                                                                                                                                                                                                |
| <b>17:00 – 17:20</b> | Break                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>17:20 – 17:30</b> | 92. Tracing Aegean Prehistory in the rocky landscape. From aerial photogrammetry to detailed recording of petroglyphs at Vathy, Astypalaia<br><i>Nikos Sepetzoglou (National Technical University of Athens); Dionysis Niotis (National Technical University of Athens); Spyros Triantos (University of Ioannina); Andreas Vlachopoulos (University of Ioannina)</i>                                                                                                                                         |
| <b>17:30 – 17:50</b> | 208. Engaging new audiences through digital dissemination of Norwegian rock art<br><i>Sjoerd van Riel (Museum of Cultural History, University of Oslo); Alexis Pantos (Museum of Cultural History, University of Oslo); Gunnar Liestøl (Department of Media and Communication, University of Oslo); Magne Samdal (Museum of Cultural History, University of Oslo); Steinar Kristensen (Museum of Cultural History, University of Oslo); Letizia Bonelli (Museum of Cultural History, University of Oslo)</i> |
| <b>17:50 – 18:10</b> | 290. Putting it in Context: Digital tools and open data to support the analysis of Scandinavian rock art<br><i>Ashely Green (Department of Historical Studies, University of Gothenburg); Rich Potter (Department of Historical Studies, University of Gothenburg); Christian Horn (Department of Historical Studies, University of Gothenburg)</i>                                                                                                                                                          |

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18:10 –  
19:00

Discussion

#### 44. Rock Solid Replicas: The Application of 3D filament Painting Technique on Pictographs in Southern Alberta, Canada.

Mavis Chan (University of Calgary)

Peter Dawson (University of Calgary)

My research examines the innovative use of filament painting, a 3D printing technique, to recreate Indigenous pictographs in Alberta, Canada. Alberta is home to over 200 known rock art sites as of 2025. Pictographs are a type of precontact painting on a rock surface, and their preservation in Alberta is under increasing threat that could potentially erase centuries of cultural expression. Ochres derived from naturally colored sediments containing iron-bearing minerals have traditionally been used to make pictographs. The animal fats and plant saps used as binders and applied to rock surfaces allow ochre to last for millennia; however, when exposed to weathering over time, ochre pictographs can fade severely, making them no longer visible to the naked eye (Andrews and Brink 2022). Over time, exposure to sunlight, wind, moisture, and temperature fluctuations has contributed to the gradual fading of many pictographs across Alberta. Human activity also poses a considerable risk. Popular sites such as the Okotoks Erratic Big Rock, for example, are frequently visited by locals and tourists. Physical alternation of the rock surfaces via climbing, accidental abrasion, or acts of vandalism can accelerate the damage. As the pictographs become harder to see, sharing their meaning and the urgency of their preservation with the public has become ever more important—and ever more difficult. Traditional photographs often fail to visualize faded imagery, and archaeologists use DStretch, a digital

image enhancement tool that uses a decorrelation stretch algorithm to dramatically improve the visibility of the faded pictographs, it also introduces discoloration to the resulting image (Le Quellec, Duquesnoy, and Defrasne 2015). Without clear representation, raising awareness and developing public engagement in preservation efforts remains a major challenge.

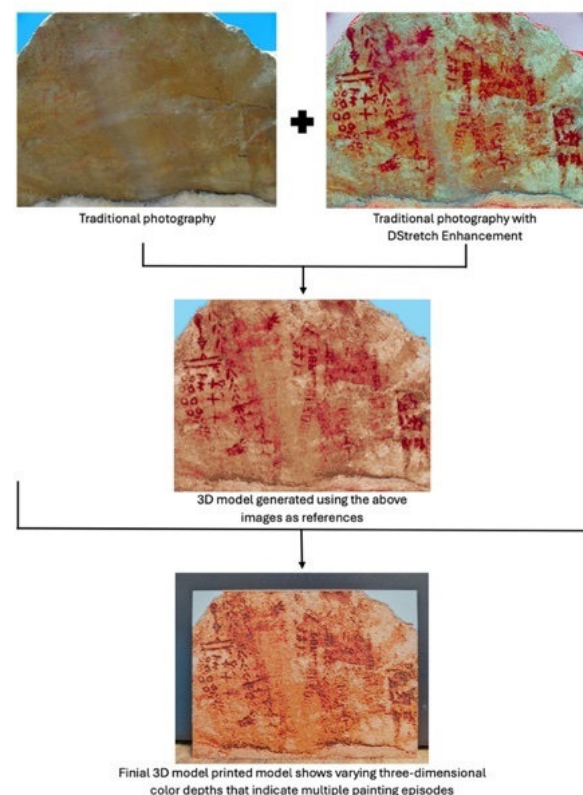
To address this gap, technologies such as 3D printing offer new possibilities for making these ancient rock art images more visible and accessible to the public. Among different 3D printing techniques, one that has not been explored is a technique called filament painting, which is a relatively recent development in the field of 3D printing. This approach allows for the creation of detailed, layered artwork by translating 2D images into 3D printable models. It involves printing flat, multi-layered panels using colored filament, where each layer represents a different tonal value or color extracted from the original image. The result is a semi-transparent blend of colors that mimics the visual qualities of a painting while offering the texture and depth of a physical object (Zagorski et al. 2025). I see the potential of filament painting in educational and cultural reproduction. The project uses traditional photography, DStretch image enhancement, and HueForge software to generate color-corrected, 3D printable models of the ancient rock art. Colour correction allow the reintroduction of the natural rock surface tones into the 3D model while using the DStretch-enhanced image as a reference. As a result, the final 3D print offers a reconstructed view of the pictographs that closely resembles their original appearance before deterioration began. This project used the acronym PRINT to represent the five workflow stages to guide its methodology. Each stage reflects a step in the transformation of fading rock art into tangible, color-accurate reproductions using 3D printing.

1. P = Photograph, referring to the traditional field photography conducted during site visits to capture current conditions of the pictographs.
2. R = Refine, in which the images are digitally enhanced using DStretch to reveal faded pictographic elements.

3. I = Interpret, the stage where color correction of the DStretched images and 3D model generation take place in HueForge, using both enhanced and reference images.
4. N = Nest, process of building the model virtually—layer by layer—through HueForge’s filament painting algorithm and Bambu Studio.
5. T = Transfer, where the digital model is physically produced as a filament painting using a multi-filament 3D printer.

I successfully conducted photography-based reconstruction and generated 3D models of the pictographs at risk at the Okotoks erratic. The resulting digital model, though, does not reflect the surface topography; it provides texture details that mimic the rock surface texture. I am also able to conduct accuracy colour correction by layer to introduce the color of natural rock surface to the digital model with the unfaded original rock art. For example, one pictograph panel (Figure 1) illustrates evidence of multiple painting episodes of vertical series motifs across time. The corresponding 3D printed model was able to show varying three-dimensional color depths for the same vertical series motif in similar regions, indicating multiple painting episodes. When conducting visual comparison between the printed model, the traditional photograph, the DStretched image, and the original pictograph on site, results show that the 3D print has a close resemblance in terms of geometric features and overall morphology, while also able to indicate that multiple painting episodes through the blending of filament colour. The successful reconstruction of at-risk pictographs demonstrates the potential of digital preservation methods to communicate the urgency of rock art loss to broader audiences. The 3D prints are given to the indigenous knowledge holder as an educational component for on-site conversation with the locals and tourists. While the 3D prints are not 100% authentic representations of the original rock art, they serve as effective tangible items that bridge the gap between inaccessible heritage sites and public engagement. The physical nature of these reconstructions allows viewers to interact with and observe details that would otherwise remain distant or deteriorating. This methodology provides a practical tool for raising public consciousness about the

ongoing loss of irreplaceable rock art heritage while simultaneously creating a tangible record for future generations. My findings suggest that the effectiveness of these reconstructions is not based on exact replication, but rather on their capacity to transform abstract concerns about cultural heritage loss into a tangible, lived understanding that inspires preservation action.



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## 56. Innovating Heritage: Digital Archaeology as a Tool for Indigenous Rock Art Engagement

*Andrea Jalandoni (Griffith University)*

Digital techniques have become essential tools in rock art research, as they enable archaeologists to produce accurate records more efficiently and cost-effectively than traditional methods (Jaillet et al. 2019). These technological developments have fostered deeper engagement with cultural heritage, allowing both Indigenous and non-Indigenous communities to connect with rock art in more meaningful ways (Brady and Taçon 2016).

Over the past decade, I have developed and implemented digital methodologies for rock art research in collaboration with Indigenous communities across Australia, Southeast Asia, and the Pacific. This work has included capacity-building initiatives, such as training Indigenous participants in photogrammetry and other digital recording techniques. In recent years, a number of these community members have actively engaged with both the research and the digital tools, often adapting them in culturally meaningful ways to support their own artistic and heritage practices. The following case studies

illustrate outcomes from community-led or collaborative digital archaeology initiatives.

The first case study is the Guam Rock Art Study (GRAS), a community-led project that inspired a Chamoru (Indigenous people of the Mariana Islands) collaborator to express her reflections on rock art through painting, culminating in a public exhibition ("Delving into Persistence"). GRAS influenced her creative practice in abstract figuration, while her artistic engagement, in turn, enhanced her ability to observe, identify, and describe the diverse motifs present in Guam's rock art. The process was a reciprocal relationship between creative expression and archaeological interpretation. She exemplifies how multidisciplinary perspectives enrich the interpretation of rock art and how creative arts offer a valuable medium for visualizing and communicating abstract, evolving ideas.

A second case study is from a documentary ("Aguiguan, Cave Art, and the Last Chamorro Stand") in the Northern Mariana Islands directed by an Chamorro documentarian. This documentary is an example of how digital archaeology can best support Indigenous-led research from conception to execution. One major contribution of the project was the discovery of ancient Chamorro rock art that had been lost to contemporary knowledge. Additionally, the digital archaeology methods offered new perspectives on cultural heritage and public engagement.

A third case study focuses on century-old bark paintings originally taken from a community in the Northern Territory, Australia. Repatriation of museum collections to their source communities remains a complex and ongoing process, often hindered by limited resources and logistical challenges (Farrar et al. 2025). While digital methods such as photogrammetry cannot replace repatriation, they enable immersive virtual reality experiences that offer alternative forms of cultural engagement. As part of the exhibition ("Art at a Crossroads: Uncover the Untold Stories of an Aboriginal Collection"), a virtual reality experience featuring digitized bark paintings was developed with the



Aboriginal community of Gunbalanya. This work has demonstrated the emotional resonance and interpretive potential of virtual environments for Indigenous communities, particularly when their voices and worldviews are central to the design.

A final case study features Magnificent Gallery, a well-known rock art site in Queensland, Australia, reinterpreted by an Aboriginal artist using a 3D model. Within the exhibition ("way to be"), the intersection of art and technology is explored as a means of reintroducing awe and wonder to this remarkable site. Projectors filled a wall with 3D models of Magnificent Gallery, allowing viewers to zoom and pan using a controller, creating an immersive experience that standard prints cannot replicate. The exhibit brochure includes an interview between myself and the Aboriginal artist, in which we discuss topics such as technology and archaeology, the idea of data as living, the dynamism of culture, challenges to primitivism, rock art as design, new ways of seeing, and the notion that culture is not frozen but still present. The exhibit offered an opportunity to present new ideas and foster fresh conversations about how we think about rock art across diverse audiences.

In conclusion, digital archaeology offers transformative possibilities for rock art research, particularly when guided by Indigenous collaboration and creativity. Through immersive technologies, community-led initiatives, and interdisciplinary approaches, these projects not only enhance data collection and interpretation but also foster meaningful cultural engagement. The case studies presented demonstrate how digital tools can support Indigenous-led storytelling, reinterpret heritage, and challenge conventional narratives in powerful and inclusive ways.

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## 64. Quantifying Image Decorrelation Techniques for Rock Art: Systematic Comparison at La Pileta Cave (Málaga, Spain)

*Rubén Parrilla (ICArEHB)*

*María Simón-Vallejo (Universidad de Sevilla)*

*Miguel Cortés-Sánchez (Universidad de Sevilla)*

Digital image enhancement has transformed rock art documentation over the past two decades, changing from manual tracing to non-contact analytical approaches that prioritize preservation. Specifically, image decorrelation techniques enable the detection of faded pigments by computationally amplifying chromatic differences between painted motifs and the substrate. However, despite widespread adoption of these methods, the archaeological community lacks systematic comparative evaluations of their relative performance under controlled conditions. Rock art images present specific challenges for digital analysis beyond preservation state. Limited chromatic palettes (ochres, reds, grays), broad spectral bands captured by digital cameras, and high correlation between color channels make difficult the robust differentiation of graphisms.

Decorrelation processes mathematically restructure chromatic data to maximize visual separability, but multiple algorithmic approaches exist with no established performance hierarchy.

The specialized literature documents diverse methodological approaches: Principal Component Analysis (PCA) remains most widely reported due to its effectiveness in dimensionality reduction while preserving spectral variance. Independent Component Analysis (ICA) offers alternative statistical decomposition, and color space transformations provide complementary strategies. More complex workflows combine multiple operations, such as stacking RGB with LHCuv color space transformation followed by PCA or ICA (Cerrillo 2024), or implementing whitening protocols across different color spaces with supervised classification (Monna et al. 2022).

Among these approaches, DStretch—a plugin for ImageJ—has become the de facto standard in archaeological rock art analysis. Its widespread adoption stems from ease of use and effectiveness for most research needs. However, its unpublished source code creates a methodological limit for its reproducibility and critical evaluation.

This study addresses this methodological gap through three specific objectives: (1) implement and standardize the main decorrelation workflows reported in rock art literature; (2) apply these methods to a selected corpus of Paleolithic rock art motifs with varying preservation states; and (3) quantitatively evaluate and rank their performance.

Empirical validation was conducted using four case studies from La Pileta Cave (Málaga, Spain), a site containing 1236 catalogued motifs spanning 30,000 years from the Upper Paleolithic through the Bronze Age. The selection includes two well-preserved motifs from Panel 19 and two zoomorphs from Panel 5.3 requiring digital processing for correct identification (Simón-Vallejo et al. 2024). This selection enables algorithm performance assessment under both optimal and severely degraded conditions.

The methodology consisted of systematic implementation of documented decorrelation approaches, including PCA-based methods, ICA variants, color space transformations, DStretch workflows, and complex multi-step

protocols. Each algorithm was applied to the four test cases using standardized parameters. Performance evaluation employed quantitative metrics assessing contrast enhancement, signal-to-noise ratio, and visual separability between pigments and substrate.

Results demonstrated significant performance variation across methods depending on motif preservation state and pigment characteristics. Well-preserved motifs benefited from simpler decorrelation approaches, while severely degraded cases required more sophisticated workflow. Finally, the quantitative ranking identified optimal method selection criteria based on specific analytical objectives and panel characteristics.

This research provides the empirical evidence for informed method selection in rock art digital enhancement. By systematically comparing major decorrelation approaches under controlled conditions, the study establishes performance benchmarks and workflow recommendations for Paleolithic art documentation. The findings contribute to standardizing digital analysis protocols while addressing the reproducibility challenges inherent in current science.

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## 92. Tracing Aegean Prehistory in the rocky landscape. From aerial photogrammetry to detailed recording of petroglyphs at Vathy, Astypalaia

*Nikos Sepetzoglou (National Technical University of Athens)*

*Dionysis Niotis (National Technical University of Athens)*

*Spyros Triantos (University of Ioannina)*

*Andreas Vlachopoulos (University of Ioannina)*

### Context:

The paper focuses on the various methods used in identifying, documenting, surveying, mapping and drawing petroglyphs that have been discovered at Vathy, on the island of Astypalaia, Greece, during the recent archaeological project (2011-2023). To this date at least 100 rock-art representations have been identified and they are connected mostly to the prehistoric period, indicating the need of the Early Bronze Age (3rd millennium BCE) islanders to depict at the rocky landscape images and symbols related to their culture. The petroglyphs are found individually or in clusters and they are located on natural limestone rock plateaus and on manmade constructions of paths or small gateways. Their surface is corroded and the quality of the glyph does not retain its original characteristics; still, in the rich repertoire of their motifs, figurative subjects, such as ships and daggers, and non-figurative themes, such as spirals and cavities, can be identified. Particularly the incised spiral motif that marks passes, pathways, streets and ramps appears to have the function of a signpost. Additionally the representations of ships are valuable for knowledge of the art of shipbuilding in prehistoric Aegean. Especially the depiction of more oared ships, documents symbols of wealth, power and skills at sea. In their entirety, these public images demand a

community basis. Even if they are worn by time and natural phenomena, the rock-art representations at Vathy constitute a fragmentary system of shapes, motifs and symbols; repeated signs, with which the community 'signposted' spaces with a specific function, imprinted emblems of power and wealth, and codified cosmological and religious symbols.

### Main argument:

The importance of natural light for the impression of the petroglyphs, their original features during antiquity and aspects of methodology regarding their documentation and interpretation today, are issues that have been crucial during the entire research. Moreover, the repetition of themes in nearby locations and the difficulty of relocating certain petroglyphs in the rocky landscape, led to their coding and numerical indexing on the topographic grid. In most cases the original morphology or architecture of the spaces that hosted the petroglyphs cannot be certain. However, special characteristics such as their orientation and position on the rock surfaces may be significant elements for their interpretation. It is probably important that petroglyphs can be distinguished into those that have been pecked on flat bed rocks and those that have been pecked on vertical rocks, though in some cases it seems that they formed a single whole, due to their proximity or common subject. It is also notable that spirals and cavities have been, in their vast majority, applied on horizontal rock surfaces. In contrast, for the representation of ships, vertical or inclined surfaces were preferred. However, many questions arise:

- How do we perceive their scattering across the landscape?
- How certain can we be about the similarity of the present state of the landscape with that of the past?
- Is the interpretation of petroglyphs affected by the significant loss of architectural structures?
- Does the different texture and tonality of the glyphs affect our impression of petroglyphs today, compared to that of the past?
- To what extent we can achieve reconstructions of petroglyphs that are difficult to recognize or interpret?

- Which methods can be more sufficient and appropriate for highlighting and recording petroglyphs today?

Questions like these were a challenge throughout the archaeological project. The use of new digital methods of surveying and recording them in situ, proved to be valuable for the research.

#### Applications:

Documenting petroglyphs requires both their recording and mapping in the landscape, as well as their detailed representation and drawing on physical scale, in order to highlight and interpret the pecked subjects - themes. To achieve these goals, photogrammetry and digital photography were used together with manual drawing and other physical ways for collecting archaeological data. The methods used are briefly described below:

- Aerial photogrammetry was used for mapping the petroglyphs in the landscape.
- Orthophotomosaics of the rock plateaus were used for drawing and digital processing petroglyphs at scale.
- Multi photography of the rock carvings throughout the day in different angles, was used to identify individual details.
- Artificial shadow testing and RTI photographic methods were used to capture the relief engravings.
- Highlighting the carvings and outlines by using washable chalk on the surface of the rock, worked in identifying the pecked areas in situ.
- In situ recording of petroglyphs with markers on transparent nylon worked together with photomosaics for the detailed drawing of the pecked subject in scale.
- Silicone squeezes of the petroglyphs were used for preparing plaster casts for further study in the laboratory.

The representation and the interpretation of the petroglyphs can be very difficult since in some cases it is not easy to understand the initial subject depicted. Drawings made for such purposes should serve certain objectives, depending on the aspects investigated each time, such as, recording the

petroglyphs preservation, attempting to reconstruct their original features, or, highlighting the typology of certain motifs.



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## 97. A multi-tool digital approach to the analysis of rock art and metallurgical symbolism in the Arabian deserts

*Jerome Kahl (University of Vienna)*

### Introduction

Digital spatial analyses conducted in QGIS, including viewshed and spatial pattern analysis, have the potential to reveal the semantic value of rock art sites related to metallurgical and funerary activities.

To date, 28 rock art sites dating from the Bronze Age to the Islamic period have been recorded at distinctive locations of the Rock Plateau of Qurayyah, one of the major oases of NW Arabia. From the extensive corpus of 192 sites containing petroglyphs, two specific themes, weapon representations and weapon-bearing figures, became the focus of a multi-tool digital analysis, aimed at reconstructing the symbolic value of weaponry and the artistic expression of metallurgists at the site. Evidence of metallurgic activity has been documented at the Qurayyah oasis since the end of the 3rd millennium BCE. These themes were chosen because they mirror bronze weaponry, which was deeply tied to personhood, functioning as indicators of status, craftsmanship, and social belonging, including kinship, ethnicity, and profession (Vandkilde 2006, 485). The depicted weapons appear both as stand-alone images and parts of human attire, communicating an artistic expression of their symbolic value within the landscape.

The integration of GIS-derived data with stylistic and contextual information demonstrates how digital landscape analysis can reveal the spatial logic and symbolic delimitations that defined the artistic sphere of metallurgists.

### Materials and Methods

The anthropomorphic themes display 107 depictions of human figures from 25 rock art contexts. Among these, 68.5% (64) are associated with weaponry: 67.2% of figures are depicted with a weapon at their waists (43), 20.3% have shields (13), 6.3% have spears (4), and 6.3% have bows (4).

Stand-alone weapons are depicted in 40 petroglyphs from five rock art sites, and can be classified into six types according to their style, pommel, shoulder, blade, and length. These depictions seem to correspond to the weapons worn by the anthropomorphic figures, and resemble weaponry attested in the archaeological record.

The methodology follows a multi-analytical approach, combining digital, stylistic, and chronological analyses. The digital component was conducted in QGIS to identify spatial patterns on the micro- and macro landscape and to assess the site's visibility through viewshed analysis. In addition, the technique and detail of the petroglyphs were examined using photogrammetry, resulting in the creation of 3D models for each context. From these models, orthomosaics were derived, enabling the visualization of the entire rock art context. The stylistic analysis has helped to understand the visual grammar, syntax, and overall style of the engravings. The chronological assessment refers to a preliminary study and included the following aspects: patination, superimposition, thematic and object-based analysis of the depicted imagery, and comparison with existing chronological frameworks in Saudi Arabia.

### Results

The analytical results show that rock art sites depicting stand-alone weapons and human figures with weapons at their waists are spatially anchored at a distinctive area of the Rock Plateau. These depictions correspond to static imagery, which does not function narratively but rather symbolically. They are dated to the Bronze Age on the basis of the similarity to physical objects dating to the same period and the lack of inscriptions and depictions of camels or horses, which traditionally date to the Iron Age.

The viewshed analysis reveals that these sites had limited visibility, being observable only from an elevated area of the plateau, thus suggesting that these rock art sites were created and consumed by individuals with exclusive access.

Photogrammetry helped to enhance the imagery, displaying that some weapon-bearers are depicted with objects resembling the stand-alone

motifs, which were thus identified as weapons. The orthomosaics facilitated the visualization of the entire context of each rock art site, highlighting spatial arrangements and superimpositions between motifs. As a result, weapon-bearers and imagery of weapons were rarely covered by other motifs, emphasizing their significance within the chronological sequence. 3D models enabled the measurement of depth, size, and proportion, indicating that the depicted weapons varied in technique, precision, and scale depending on their location. Some engravings exhibit technical detail, small size, and realism, while others are overproportioned and abstract, reflecting intentional variation in depiction.

#### Discussion

The rock art sites depicting stand-alone weapons and weapon-bearing figures are concentrated near a semi-circular tower, designated as Area M, where metallurgic activities took place in the Early Bronze Age (Luciani 2023). Contemporary funerary activities at the foot of the plateau in Area B and C contain bronze objects and are linked to the same community involved in metallurgic practices. Apart from their commonalities with metallurgy, all these three areas are gated by architectural boundaries such as walls, which physically and symbolically delimit access. The restricted visibility of the rock art sites reinforces their exclusivity. These images were intended only for those who had access to these gated areas.

The metallurgical activity on the plateau corresponds to an economic sphere that intersects with a funerary sphere, in the tombs located at the foot of the plateau. The funerary contexts in Area B and C illustrate how metallurgists presented themselves through metal objects that symbolized their status, profession, and social identity. Within this framework, the concentration of weapon imagery may be understood as a spatially anchored collective memory, a symbolic sphere, through which the same agents expressed likewise values of social identity and professional affiliations.

Similarly, in the Negev Desert, petroglyph sites depicting “crescent-headed figures” were connected to Bronze Age copper traders, based on their spatial relation to trade routes, weapons design, and associated archaeological

contexts (Schwimer and Yekutieli 2021, 239–240). This case, like Qurayyah, shows that weapon imagery often expressed professional identity and social meaning rather than scenes of conflict.

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## 106. If these walls could talk. Exploring the potential of multivariate statistics to investigate Egyptian Old Kingdom elite tomb iconography.

*Christel Birkmann-Little (Leiden University)*

#### Introduction

Egyptologists have long appreciated that iconography in Old Kingdom elite tombs can convey information about dating and/or provenance of a tomb or tomb fragment. Scholars are continually encountering the same roadblocks, however: remains are fragmentary, the data sets small, and there is always a need for secure anchor points. This paper proposes a novel approach to address these issues, using the iconography of Memphite tombs as a case study for multivariate statistical analysis. This type of analysis for



iconographic information, which is discrete in nature, remains largely underutilised in Egyptology. A novel approach for extracting and analysing iconographic information is explored in an effort to understand the relationships between various iconographic features in Old Kingdom elite tombs and investigate whether these features have the potential to act as dating and/or provenance predictors. This paper lays the groundwork for understanding how to deal with this kind of information and paves the way for further exploration of how multivariate statistical solutions can be applied. Rather than a purely data-driven study, this paper employs the synergy between statistics and Egyptology to identify (hidden) relationships between iconographic features.

#### Methods and materials

A defined scope of Memphite tombs and iconographic features with proven dating/provenance relevance is used in this study to establish an appropriate statistical method. The offering table scene is used as a starting point with features from other scene types included at later stages of the study. Previous studies mapping specific iconographic features of Old Kingdom elite tombs, such as those of Cherpion (1989) and Swinton (2014), provide the basis for this study. These studies coupled tombs and their features to dating anchors and created artificial 'lifespans' for certain iconographic elements. This paper steps away from this two-dimensional approach, removing the need for dating anchors by simply recording the presence (or not) of selected features and analysing these as discrete datapoints. Such an approach was hinted at by Seidlmayer (1997) but not pursued. Multiple correspondence analysis is used to understand the relationships between iconographic features and how certain features perform in discriminating between tombs. Object scores from these analyses are then leveraged to observe how tombs cluster together when considering their iconographic profile. Various cluster techniques, including Hierarchical cluster analysis and K-means cluster analysis are employed to this end. The clustering of tombs based on their iconography is the preliminary outcome of this paper.

A second, exploratory component considers whether iconographic data can be employed in a prediction model. This paper considers the use of logistic regression to predict the date and/or provenance of a tomb or tomb fragment.

#### Results

This study successfully extracts iconographic information in the form of binary data from Old Kingdom elite tombs and analyses it using multivariate statistical methods. The results confirm that iconography can separate tombs based on chronology and, to some extent, provenance. This is most evident when considering the offering table scene in isolation. Interestingly, introduction of iconographic features from other scene types in tombs dilutes chronological and/or location clustering. It also becomes apparent that certain iconographic features are strong discriminators, such as the items to be found on and around the offering table, whilst others barely contribute, such as the orientation of the deceased.

The strength of the offering table scene in clustering tombs with similar iconographic profiles also extends to its value in prediction models, with a model based on 'strong' discriminating features able to correctly allocate 94% of tombs to an appropriate temporal group. It is also valuable in predicting provenance, with 80% of tombs receiving correct allocation. Models built including features beyond the scope of this scene were either unstable or had predictive capacity less than chance.

#### Discussion

This paper shows how a statistical approach to iconography can reveal previously hidden relationships between iconographic features, stimulating Egyptological discussion. The clustering of tombs invites research into why certain iconographic profiles appear in certain tombs, instigating consideration of the consumption of this type of art and how this influenced the creation of new works. Factors such as individuality, the influence of artists/workshops, proximity to other tombs, and socio-economic influences can be explored in more depth. Additionally, the rigidity of the offering scene,

previously considered a limiting factor, now becomes beneficial for dating and/or location prediction of unknown tombs and fragments.

Statistical analysis overcomes the fragmentary nature of remains by focusing on statements of likelihood, providing a level of transparency that discourages sweeping conclusions. The ‘small’ size of datasets in this field remains a challenge, however this study shows that there are several methods that can still be leveraged successfully. Finally, the method of this research has shown how tombs and their iconographic features can be decoupled from any dating or provenance assumptions, removing the need for secure anchor points. The data has been allowed to speak for itself rather than having historical assumptions be perpetuated.

The Egyptologist stands to gain a complement to their contextual knowledge by having a method to explore previously unobserved tendencies and substantiate findings with unprejudiced statistical data

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### 119. Visualization of bas-reliefs from three-dimensional objects – example of ornaments on the heads of moai kavakava – wooden figurines from Easter Island

*Rafal Wieczorek (Uniwersytet Warszawski)*

*Paul Horley (Cimav Campus)*

Three-dimensional artifacts of material culture may feature ornaments or paintings that are challenging to represent in a two-dimensional format. A notable example of such objects are the moai kavakava wooden figurines from Easter Island. These statuettes depict anthropomorphic figures that often display ornamental bas-reliefs on their heads. The decorations portray humans, octopuses, birds, as well as other difficult-to-classify or chimeric beings. Because these designs frequently extend around the entire head, they cannot be captured in a single photograph, and publications on the subject typically rely on hand-drawn illustrations to visualize the bas-reliefs.

The goal of our research was to develop a methodology enabling a consistent and repeatable two-dimensional representation of these bas-reliefs—one that could also be applied in the future to new, previously unstudied objects. To achieve this, we generated three-dimensional models of moai kavakava heads, from museum collections across the world, using photogrammetric techniques. The 3D models were transferred from Agisoft Metashape to Blender, where their texture was then mapped onto the surface of a sphere. In the final stage, this spherical surface was visualized in two dimensions through a process analogous to cartographic projection.

This approach can also be applied to other cases where drawings or engravings cover a surface approximating a sphere.

### 123. Stirring the hornet's nest: demonstrating the ritual dimensions of Northwestern Amazonian petroglyphs through geometric morphometrics

*Samir Chavarro-Belafonte (University of Tübingen)*

Rock art panels are some of the archaeological features most directly connected to worldviews and belief systems, important aspects of a complete picture of past human societies otherwise hard to recover or study empirically. The study of Amazonian rock art has experienced spectacular advances increasingly attracting public and media attention, built over decades of ethnological research alongside native communities producing a complex body of theory on the meaning of rock art, and how it reflects the collective values and goals of local communities, which have tangible effects on politics, policy, and ultimately, human-environment relationships.

Correlating rock art to direct chronologies remains a hard challenge, doubly so for petroglyphs which, unlike the paintings comprising the absolute majority of reported rock art sites, cannot in principle be dated estimating ages of added material to a substrate, the rationale behind all currently reliable dating techniques. This has led to charges of rock art studies being speculative, unverifiable, and non-scientific, so archaeology as an empirical discipline rarely considers rock art as a true element of material culture for this reason, rather focusing on aspects of human subsistence and technological change which, although informative, present a fragmentary view of the human past and rely on evidence which, due to their nature (organic material, small-sized lithics and pottery, etc) is quickly lost in environments such as the Amazon rainforest.

Here are presented the results of a quantitative analysis of petroglyphs found in five Colombian cultural heritage site clusters in the Northwestern Amazonia (NWA), an area historically difficult to survey due to logistical challenges and because it still is one of the main theaters of the Colombian armed

conflict. Some of them -Piedralinda and Cocoviejo-, are reported for the first time as archaeological sites, and others -Angostura II and the Araracuara sites- have already been proven pivotal for understanding the early settlement of the Amazon Basin and how tropical rainforests have been subject to anthropogenic impacts since at least the early Holocene if not before, with dense occupations occurring at the Middle Holocene (8200-4200 BP) just before the adoption of agriculture and pottery.

A replicable semi-automated motif tracing protocol using orthophotography generated with drones and digitized tracings from older reports, followed by a geometric-morphometrics based principal component analysis, was used to perform quantitative analysis of anthropomorphic petroglyphs from these sites.

This quantitative approach empirically demonstrates significant morphological similarities between the Piedralinda and the Araracuara anthropomorphic motifs, a find consistent with previously proposed relationships between the putative creators of these rock art assemblages based on ceramic typologies and reconstructed local foraging strategies. Also shown is a significant morphological difference between the El Encanto anthropomorphic carvings and the rest. All this suggests that the observed differences can be explained in terms of a shared know-how for replicating motif "styles" within the framework of a belief system which was either inherited or adopted across the NWA, rather than by simple geographic or ecological constraints, since the connections were established across different watersheds, biomes, and regional lithologies which all potentially could have affected the distribution, engraving techniques, and composition of the anthropomorphic motifs.

Informed discussions on the ritual dimensions of Amazonian rock art are thus possible through the combination of computer-based quantitative methods with Amazonian ethnographic research. In the specific case of the NWA petroglyphs, a proposal is made to predict chronologies based on absolute dates from similar representations in the same or other media (such as paintings

and pottery imagery) at nearby archaeological sites, and chronologies based on diachronic linguistics, hopefully to be confirmed by future excavations on some or all of the mentioned sites following geoarchaeological best practices in order to guarantee site integrity.

The art corpus examined here is presently argued to have been produced in connection with the Yurupary initiation rites to introduce young people to the mysteries of the religion around the hornet-coded deity known as Kuwai, and other regional belief systems, a key aspect of the emergence, dispersion, and evolution of family languages, social organizations, and agriculture regimes in this region from roughly 4000 years ago up to the arrival of European explorers.

Here is demonstrated the feasibility of conducting quantitative studies of petroglyphs, overcoming the limitations of purely qualitative, hermeneutical approaches to rock art while providing them with empirical evidence required to support their insights. It is also highlighted how the method allows to (re)use data obtained from past fieldwork, which sometimes captures details of the motifs no longer available due to accumulated damage to the archaeological sites, and also reduces reliance on costly instruments often requiring special technical/logistical support, and digital literacy skills not always available for workers and researchers on the field and in underprivileged communities, most likely to interact with rock art, and the most interested and affected parties in its preservation, increasingly threatened by the effects of economic inequalities and human-driven climate change.

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## 150. Imprints of Time: Reconstructing Prehistoric Expressions Through Digital Lenses

Ankita (Banaras Hindu University)

The medium of art extends beyond offering a mere sensory experience, but also serves as a profound form of expression. As ancient communities evolved and created several tangible and intangible artefacts, communities engaged in the practice of painting on rock surfaces, creating invaluable troves for understanding their individuality, societal practices, traditions, and cognitive abilities. Rock art studies provide a multi-faceted understanding of archaic societies, but the primary challenge in studying prehistoric art lies in its gradual degradation due to several natural and artificial factors, countering which the digitisation of rock art becomes an essential practice for its study, interpretation, analysis and heritage preservation.

This paper focuses on the rock paintings of the Raghubirgarh site in District Kaimur, Bihar, which we have selected for digitisation. The initial exploration of the Kaimur rock art shelters was undertaken by Anand Kumar (1991–92) and A.K. Prasad (2001, 2003–04, 2005–06, 2010). This investigative endeavour was later advanced by A.K. Prasad and Sachin Kumar Tiwary (since 2007) unfurling new insights for future researchers. Geographically, the Kaimur ranges lie in the eastern region of the Vindhya formation, extending between Sasaram, Bihar, in the east, to Satna, Madhya Pradesh, in the west, through

Uttar Pradesh. The rock shelters are situated within deep gorges carved out by torrential hill streams (Tiwary, 2019). Its geographical alignment with sub-tropical climatic conditions induced diverse habitats and species, evidence of which can be derived in the form of the spatial distribution of varying motifs across shelters. These offer a tactile display of diverse pictographs and petroglyphs, primarily reflecting anthropomorphic figurines, community lifestyle, war sequences, weapons in use, cultural practices, pastoralism, patterns, and shapes. There are instances of depicting movements and X-ray-like human portrayals reflecting cognitive advances. Some compositions find themselves in secluded spaces, while others are cluttered and unevenly distributed. The presence of superimpositions is widespread on both crooked and undulating soft surfaces.

Image processing software such as DStretch and Adobe Illustrator has been leveraged to identify less visible motifs and patterns otherwise imperceptible to the naked eye. In accordance with the algorithmic principles outlined by Harman (Harman 2011), each photograph was processed depending on the levels of rock art visibility and the light source, with different enhancement combinations. The YRD, YRE, and RGB colour spaces were systematically applied because they showed the highest sensitivity to red ochre pigments, which are dominant in the Kaimur shelters. (Valdez-Tullett 2018). Images that deviated from this workflow due to uneven lighting, shadow interference, or topography underwent hue and contrast adjustments for clarity. In cases of background noise where the visuals failed to distinguish themselves, the color balance feature has been applied to images before any decorrelation stretch enhancement. The final stage in the processing includes cross-checking with the unaltered photograph to analyse the distribution of false colours and prevent results compromising originality. Given the interference of the background and shadows, the blend of colour spaces with these plugins works best in certain situations. Hence, DStretch proves to be a game-changer for deciphering rock in its ability to let the colours coexist independently by separating them instead of limiting itself to RGB colour spaces.

From the visual standpoint, the implication of Adobe Illustrator as a designer tool connects the dots in achieving visual cohesiveness and ushering interaction. After enhancement, each motif was digitally traced and reproduced in black bold outline using the 3-point Round Brush tool from Adobe Illustrator. Tracing was performed directly over processed DStretch outputs while maintaining the same brush width, stroke profile, and smoothness settings across all motifs to ensure visual consistency.

Digitised processes enable the study of broader aspects of pictorial depiction and their spatial distribution, colour variation in pigments, stages of weathering, and climatic fluctuations. The heritage of rock art creates a core understanding of the initial societal development that we have eventually become a part of. The study aims to evaluate the extent of variation that digital enhancement creates in fragmentary rock art shelters on the verge of erosion, establish a cost-effective and time-efficient workflow for rock art digitisation, and maintain archival depositories of digitised images to conserve their intrinsic value and make them accessible for future research.

What remains in question is how to preserve a potential rock art site that continues to remain in a state of neglect. Despite being significant for studying cognitive and cultural advancements, frequent human encroachment has reduced it to mere picnic and animal grazing spots defaced by graffiti. Additionally, factors such as water percolation, discolouration, mud wasp infestation, and weathering have posed a serious threat to deterioration. Therefore, the digital preservation of such endangered sites becomes not only a methodological necessity but also a cultural responsibility to safeguard the visual legacy of our prehistoric ancestors.

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## 163. Using rock art and Species Distribution Models to understand climate change in Predynastic Egypt

*Sebastián Maydana (University of Liverpool)*

### Context

The period of Egyptian prehistory known broadly as "Predynastic" encompassed some of the most enduring changes in the history of northeast Africa, not only regarding social organisation but also in terms of environmental transformation. Human populations migrated to remain close to water sources, mainly the Nile, and there was a general mobility process from north to south. The transformation of the environment, from a savannah to a desert, also developed from north to south, and so did the distribution of wildlife species. Dramatic climatic changes took place in North Africa during the Holocene, with savannahs covering swathes of the Sahara during the Green Sahara phase. However, the timing, magnitude and consequences of these changes remain poorly understood. A largely untapped source of evidence in palaeoecological modelling of Holocene Sahara is the rich heritage of rock art found throughout the region, which offers amazing possibilities for gaining insight into the social and climatic processes of the time. How did these processes affect each other? Were they all the effect of climate change? Or did human activity, for instance more intensive hunting or the development of pastoralism, also modify the habitats so that animals were pushed further south?

Thanks to the enormous development of species distribution and climate models in recent years, these questions can now be answered, but the answers are not always new. In fact, in Egyptology, the main hypotheses proposed between the 1950s and the 1980s relied heavily in the effects of climate change on human social organisation (e.g. Hassan 1988); most of these hypotheses, however, were never proven, and they were abandoned for two reasons: one was that there were few tools at the time to actually test them, so they remained mainly in the realm of speculation; Secondly, because they actively underestimated the relationship between humans and the environment, thinking of it as a one-way relation in which humans barely "responded" to climatic contingencies and extracted resources. In other words, they were deterministic, and for this reason they were abandoned as soon as more multi-causal explanations became the preference of academic circles.

### Main Argument

Species distribution models are a relatively new technology (Guisan et al. 2017) that has never been used to study rock art. This cross-disciplinary investigation integrates species distribution modelling, archaeozoological data and pictorial evidence from rock art to establish likely scenarios for past changes in biodiversity, human-animal relations and societal organization in response to climate change. In this sense, it focuses particularly on the Predynastic Period of Egypt (ca. 5300-3000 BCE), which was a time of profound climatic and societal changes, leading to the formation of the pharaonic civilization. In this communication, I intend to present the preliminary findings of my on-going PhD research, in which rock art studies are paired with species distribution models to reach a better understanding of the processes that happened during the Predynastic Period.

### Applications

By using powerful, up-to-date modelling tools to hindcast possible interactions between humans, animals and the environment, this research aims not only at testing old hypotheses but at developing an explanatory model that



accounts for the extraordinary Predynastic change in society and its relationship with the environment, hopefully providing important insights about the general impact of human mobility in animal distribution and sustenance. Recent studies (Bro-Jørgensen et al. 2025) have used species distribution models to identify certain species in Predynastic iconography, showing that this new technology has useful applications in the field of Egyptology. However, the full extent of its applications is yet to be discovered. Here I present some of the possibilities in which rock art studies are able not only to “inform” species distribution models, but become a source of hypotheses testing and of improving our knowledge of the times in which these petroglyphs were created.

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## 181. Written on the Landscape: A Quantitative Analysis of Competing Territorial and Mobile Strategies at Ḥimā

*Giacomo Fontana (Texas Tech University)*

*Alessia Priolella (CNRS, UMR 8167 - Orient & Méditerranée)*

The location and significance of rock art and epigraphic remains in the Arabian Peninsula have traditionally been studied through qualitative field observations. While effective for interpreting local patterns, this approach faces limitations when addressing the distribution of thousands of inscriptions across broad spatial and temporal scales. This paper introduces a quantitative framework employing spatial point process models (PPMs) (Bevan 2020) and GIS-based environmental modeling to analyze 22,209 rock art inscriptions from 1,793 panels in the Ḥimā region, southwest Arabia (MAFSN dataset) (Priolella 2022).

The analysis moves beyond preferential placement to reveal competing geopolitical strategies in a landscape of overlapping territorial and mobile populations. We demonstrate that Himaitic and South Arabian script users inscribed according to fundamentally different spatial logics. Himaitic script users employed a territory-based placement at higher elevations, away from natural corridors, marking likely residential zones. Conversely, South Arabian script users utilized a route-based placement on natural movement corridors with high visibility, marking waypoints on larger networks.

The models demonstrate significant spatial segregation and negative within-panel association between the two scripts, suggesting maintained political boundaries despite landscape overlap. Mixed panels, occurring at high-visibility interface zones, are interpreted as contact points where territorial and mobile groups negotiated shared space. The analysis also investigates diachronic processes, modeling how earlier inscriptions may have shaped the clustering or dispersion of later ones. This study demonstrates how quantitative spatial analysis of inscription practices reveals landscapes as contested

spaces where power and mobility are materially expressed, offering a replicable methodology for comparative studies across diverse epigraphic landscapes.

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## 208. Engaging new audiences through digital dissemination of Norwegian rock art

*Sjoerd van Riel (Museum of Cultural History, University of Oslo)*

*Alexis Pantos (Museum of Cultural History, University of Oslo)*

*Gunnar Liestøl (Department of Media and Communication, University of Oslo)*

*Magne Samdal (Museum of Cultural History, University of Oslo)*

*Steinar Kristensen (Museum of Cultural History, University of Oslo)*

*Letizia Bonelli (Museum of Cultural History, University of Oslo)*

The Museum of Cultural History (MCH), University of Oslo, has the administrative responsibility for over 2000 petroglyphs in southeastern Norway. The figures range from animal figures representing moose, whales and other wild animals, to boats, people and sun-figures. In the Nordic countries, it was once common to paint rock carvings to give the public the opportunity to see the figures regardless of lighting conditions, but this practice has become

controversial for several reasons (Bjelland and Helberg 2006). Since painting is no longer practiced, we must investigate alternative methods to disseminate the figures and create meaningful experiences for visitors. In this presentation, we will discuss several avenues into the use of technology to create such experiences for the public.

#### Methods and materials

The MCH is collaborating with local authorities to disseminate rock art in their jurisdiction to the general public. In 2025, work commenced on several sites across southern Norway. 3D documentation produced with an Artec Leo structured light scanner, photogrammetry and Gaussian splats were combined with the detailed interpretations already held in the museum's archives. By exploiting common 3D and GIS toolsets, we were able to bring these interpretations into 3D space, allowing the visitor to switch between the non-painted and digitally repainted versions.

Combining this data with publishing platform ESRI StoryMaps and 3D rendering programs provided a powerful tool for communicating some of the hard-to-experience characteristics of these carvings, such as the dramatic effect the position of the sun, as well as contextualize the rock art and research in simple and accessible ways.

Another project at the MCH together with the Department of Media and Communication at the University of Oslo aims to better communicate the people behind the petroglyphs through innovative technologies involves the use of the Unity-based SitSim (Situating Simulations) Augmented Reality platform (Bishop et al. 2025). Still in development, this project will deliver a mobile application which will allow visitors of a stone age rock art site in central Oslo to experience a 3D animated scene of a stone age person carving the petroglyphs, as well as a reconstruction of the surrounding environment around 7000 years ago.

#### Results

Although ongoing, some preliminary results have been positive. Firstly, these technologies allow a more interactive form of dissemination. Rather

than visitors being passive consumers of information from a sign or brochure, some technologies can include them in the process or exploration and interpretation of petroglyphs. This is especially true for the second project that draws on the potential of Augmented Reality to engage the visitor with their surroundings. Secondly, these technologies allow us to go beyond reality and into the realm of reconstruction and hypothesis testing. By integrating many types of data for the reconstruction of the stone age landscape but, importantly, also considering the people who created the petroglyphs, we are forced to take a holistic approach to rock art.

#### Discussion

In the national strategy for protection of cultural heritage, the Norwegian Directorate for Cultural Heritage (Riksantikvaren) specifically mentions method development in the documentation, preservation and dissemination of rock art as a prioritization for cultural heritage management in Norway, as well as a need to further develop documentation methods and to utilize new documentation technologies for less invasive dissemination. Many petroglyphs are situated in vulnerable and remote nature areas that require careful management and benefit from methods that allow visitors to virtually visit the sites. Notable examples from Norway include “Virtuelle Vingen” and the 360° virtual tours at the Alta World Heritage Center for Rock Art.

We believe that many of the approaches we employed in our projects can be directly transferred and implemented on other projects related to petroglyphs both in Norway and the rest of the world, and provide a useful base for more advanced, and integrated experiences as mixed realities technologies continue to mature.

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## 212. A Spatial Life: Rock Art Distribution and Visibility among Mobile-pastoral Societies in the Mongolian Altai

*Michael Fisher (Max Planck Institute of Geoanthropology)*

*Dovydas Jurkenas (Max Planck Institute of Geoanthropology)*

Skepticism of the theory that sociopolitical complexity emerged on the Mongolian steppes in the Late Bronze Age generally points to the lack of typical hallmarks such as architectural remains of administrative apparatus. However, it often fails to consider what the geospatial contexts of thousands of ritual and funerary monuments and tens of thousands of petroglyphic images might imply. Prehistoric rock carvings in the Mongolian Altai Mountains depict a wide range of subjects, including wild and domesticated species, figural scenes such as horse masters and birthing women, and technologies of their time such as chariots and stirrups. The debate over the nature and timeline of emergent social complexity among mobile pastoralists in Mongolia must necessarily account for the prevalence of small, seasonal, impermanent settlements relative to sedentary sites, often by combining analysis of the ethnographic record with study of extramural monumental and artistic remains. It nevertheless rarely includes formal study of the spatial relationships between seasonal habitation spots, funerary monuments, and rock-art clusters, which can tell us about the contexts of social messaging and their potential role in the development of incipient social complexity in Mongolian antiquity.

The 'dependency hypothesis', as summarised by Houle [1], states that multi-tiered, complex sociopolitical organisation only emerged in the Mongolian steppes as a response to sedentary state polities of the Iron Age (ca. 200 BC). Complex Systems Theory, however, views sociopolitical development as an adaptive process derived more from micro interactions than macro structures [2]. A degree of complexity is likely to have emerged through the broader social networks established as a by-product of Late Bronze Age mobility technologies such as horse domestication (ca. 1500 BC) [3]. Indeed, the appearance and growing prevalence of horses and horse gear in petroglyphic art over the course of the Bronze Age intimates their increasingly significant role in prehistoric Mongolian society, while the variation among burial monument sizes by the Late Bronze Age suggests a shift toward social differentiation. Thus, burial distributions factor heavily into interpreting the nature of prehistoric social organisation in Mongolia, but the co-location of rock art clusters with funerary monuments raises the question of whether their spatial relationship signifies an important role for petroglyphs in promoting increasingly complex modes of social organisation.

In this paper, we combine field survey and remote sensing data collected under the Mongolian Archaeology Project: Surveying the Steppes (MAPSS) in order to help address the question of whether Altai rock-art distributions relative to habitation and funerary sites can tell us about social organisation of prehistoric mobile pastoral communities. We document the locations, slope aspects, facing directions, and types of petroglyphs in relation to ancient monuments, ancient campsites, and modern campsites, at both local and micro-regional scales. We collect the data in a GIS and apply viewshed analysis to determine and compare variable degrees of visibility between rock-art clusters, funerary spaces, and possible settlement areas. We approach the topic of emergent social complexity from a Complex Systems Theory perspective, viewing funerary monuments and rock art as mediums for interaction whose dispositions can reveal community boundaries and integration.

We initially hypothesized that the spatial proximity of petroglyphs to dense distributions of Bronze Age burials signified overlap between artistic messaging, funerary practices, and social organisation. However, rough demographic estimates based on ethnographic campsite data suggest that the densely populated burial grounds would have likely been the cemeteries of larger communities, rather than being limited to serving the nearby seasonal occupants. On the other hand, viewshed analyses show that visibility of the rock art panels is circumscribed to the local campsites. Thus, our revised working theory is that certain mountain chains may have held a dual significance, one as a sacred burial ground for the larger Bronze Age community of this region, and one as a space that is topographically conducive to campsite habitation and locally focussed artistic messaging.

Within a Complex Systems Theory framework, the analytical outcomes of this research represent a multi-tiered sociocultural system, with seasonally migrant communities locally defined but still integrated into a broader supra-community that, over time, developed greater centrality and commanded increasing amounts of excess labor. Our preliminary results thusly follow Houle in challenging the 'dependency hypothesis' and are consistent with the interpretation that vertical integration processes among mobile pastoral groups in Mongolia began long before the horizon of empires.

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## 220. Desert to the Sea: Reconnecting Visual Communication Systems across the Western Desert

*Jo McDonald (CRAR+M UWA)*

### Introduction

Aboriginal occupation of north-west Australia spans more than 50,000 years, with the open social networks of the Western Desert cultural bloc enabling sustained mobility and intergroup communication across the arid zone. Dreamtime mythological narratives (Jukurrpa) and rock art create a robust information network that encodes knowledge about Country, water and identity. Our collaborative project on-country provides access to remote sites for communities managing extensive cultural landscapes. The project focuses on two-way science and intergenerational knowledge exchange and is structured in four research nodes: 1) Rock art and Jukurrpa: identifying cultural landscapes; 2) Fire and plants - Traditional Ecological Knowledge-Western Science; 3) Collections; and 4) Managing cultural landscapes: Intergenerational knowledge transfer, two-way science and data mobilisation.

The research nodes are focussing on better understanding:

1. How mythological narratives (Jukurrpa) of Australia's deserts enable the transmission of knowledge for navigation through water-limited environments?
2. How rock art and songlines support continuity of cultural knowledge across generations in desert environments?
3. How modern comparative collections (plants, residues, charcoal) allow us to better understand the archaeological record, ensure knowledge transfer between generations, and develop new TEK-based management regimes?
4. What new insights emerge when legacy datasets and material culture collections in museums are integrated with high-resolution spatial and visual documentation?

### Context to Research

The Desert to the Sea Project draws on the digital transformation of rock art research to generate both scientific and social value. Researchers across the four nodes are building live, integrated datasets to answer our research questions. In this paper I focus on exploring the relationships between rock art, water and Jukurrpa and how digital datasets can support this research. To do this we are blending digital innovations with western approaches integrated with Indigenous knowledge. The relational database being mobilised is allowing a greater depth of analysis and revealing systematic variation in motif style(s) and location. This finer detail, combined with the contextualization provided by our indigenous hosts is leading to more detailed questions being asked about signalling, mobility and cultural attachment (McDonald and Veth 2013).

### Results

Rock art research on the Desert to the Sea Project is generating digital datasets of great scientific and social value. We are already seeing the transformative impact of using digital methods in complex multidisciplinary endeavours. Key insights explored in this paper include:

- How an increasingly large and flexible digital dataset is allowing more detailed analysis of trends observed in marking and communication across landscapes, initially theorised 20 years ago (McDonald 2005).
- How image enhancement (e.g. hyperspectral and DStretch) is enabling the visualisation of weathered and/or obscured motifs – leading to the detection of previously unrecorded content and the refining of superimposition and style sequences.
- Ways that 3D modelling and the capture of rock art sites and assemblage morphology are assisting with understanding superimposition sequences and providing viewing opportunities for partner communities who are unable to visit some of these remote locations (Davis et al. 2017).
- Combining Western Desert Traditional Ecological Knowledge with GIS modelling is allowing for new knowledge generation around deep time signalling behaviour, in particular how people have used songlines and rock art to remember the social geography of water sources in the desert.

## Discussion

The Desert to the Sea Project is transforming rock art research to generate both scientific and social value. While still a work in progress, we have:

- Improved documentation and data resolution and increased our capacity for rock art research and management.
- Achieved digital reunification of dispersed records and the recording of new site complexes, enabling more detailed stylistic analyses across different range systems, revealing interaction and identity exchange between different dialects of the Western Desert language groups.
- School-focused on-Country programs, with digital visualisation supporting hands-on direct engagement with intergenerational learnings.

Indigenous data governance and cultural resurgence are being facilitated by digital systems with secure community access, while two-way science and intergenerational learning are being expedited using a digital platform. Our research is demonstrating that rock art functioned as visual mnemonic, reinforcing Jukurrpa and spoken narratives, and enabling important information about cultural attachment to water to be encoded across Country. These results provide new evidence for rock art correlating with important water locales and routes. By combining digital methods with cultural and scientific expertise—this project is amplifying the research outputs. Technology deployed in this co-designed research program will ensure that knowledge embedded in the landscape remains active, authoritative, and Indigenous-led.

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## 244. Rock, Paper, Mesh: Integrated Approaches to Recording Desert Rock Art

*Emma Beckett (UWA)*

Desert to the Sea is a large multidisciplinary project that includes an investigation of rock art in the deserts of Western Australia. Working closely with our three partner organisations Murujuga Aboriginal Corporation (MAC), Mungarlu Ngurrarankatja Rirraunkaja Aboriginal Corporation (MNR) and Jamukurnu-Yapalikurnu Aboriginal Corporation (JYAC), we are remobilising large quantities of previously recorded data (analogue and digital) and blending this with new data collected as part of on country trips. Here I consider our approaches and the importance of planning for and integrating data storage and repatriation into project design.

The project employs a suite of datasets, digital documentation and analytical tools, including:

- Previously collected or 'legacy' site information consisting of photographs, maps, hand-drawn panel and motif illustrations. This includes data collected by Alfred Canning when he surveyed the Canning Sock Route in the early 1900s and crayon drawings created by traditional owners and collected by early anthropologists in the 1960s.
- New information collected during site visits in partnership with Ranger groups and Traditional Owners who are culturally responsible for Country.



- Mobile field platforms for collecting new information as well as integrating georeferenced legacy data into in field workflows.
- Terrestrial photogrammetry and iPhone LiDAR to ensure 3D documentation of places where possible.
- Remote sensing (UAV and satellite) to situate documented sites and characterise their broader contexts.
- Integration of datasets into a SQL database accessed by a web application to ensure information accessed by researchers is live and up to date.
- Transfer of datasets into digital knowledge management systems co-designed with Traditional Owners to ensure data sovereignty and visibility in ranger operations.

The creation of an integrated, consistent and useful dataset is challenging. Even when aspirations are aligned what is ‘useful’ is a matter of perspective: a problem further complicated when there are temporal gaps and technological shifts in data collection. As technology has improved, so too has the volume, resolution and size of the data. Solutions that integrate data across multiple scales using hierarchical frameworks provide allow more flexibility but require ongoing maintenance. This enables a tangible examination of how data collection can and has changed and how different forms of data can be used, consumed and shared by researchers, stakeholders and (when appropriate) the public.

Changing technological approaches to recording allows for different levels of interaction with the digital record. With this comes a broadening of the audiences and benefits that can be achieved through mindful dissemination of the data. Accessible, integrated and experiential records can be created with increasing ease: something that both enriches and complicates the recording and storing process. This does not negate the importances of attribute information, sketches or photographs (analogue and digital), rather it is about maximising value can be used to create a variety of additional outputs which can assist in communication, interpretation and making these elements of these places, where culturally appropriate, accessible.

This collaborative co-designed partnership includes digital repatriation, the aim of which is to enable Traditional Owners to be strategic in managing their heritage estate in the face of increased development pressure (475 live or pending mining tenements across the MNR and JYAC native title areas), and remoteness-related resourcing challenges. A robust digital system will allow Traditional Owners to assert custodianship and monitor threats with greater precision. Ultimately, the Desert to the Sea Project is demonstrating that Indigenous knowledge systems have always been dynamic, adaptive, and technologically innovative—qualities essential for their continued vitality.

This work also highlights the importance of developing strategies for long term storage and (ongoing) repatriation of data that align with the guidelines that properly acknowledge and protect Indigenous rights by adhering to CARE (Collective Benefit, Authority to Control, Responsibility and Ethics) principals. Analogue and digital datasets both require curation and maintenance to ensure they remain accessible into the future. Planning, time and ongoing consultation is needed to ensure these become a reality, rather than empty rhetoric. Our research is governed by a collaboration agreement that is focused around Indigenous decision making and the importance of Indigenous Cultural and Intellectual Property (UNDRIP 2007). This work has international relevance for researchers who want to consider how to develop approaches that centre Indigenous rights, Arid-zone cultural resilience, landscape-scale visual communication and co-designed digital heritage infrastructures.

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## 287. Hunting arts: informing the spatial organisation of prehistoric rock art through indigenous knowledge

*Oliver Vogels (University of Cologne)*

There is a general agreement that hunting was essential for human evolution and social development in prehistory (Hill 1982). To date, hunting has been central in numerous archaeological publications that seek to explain the location and abandonment of archaeological sites, as well as the subsistence strategies, the survival resilience and social development of early human societies. Nonetheless, such works are often limited by a lack of understanding of traditional hunting practices, i.e. on foot, with bow and (poisoned) arrow. The projects "Indigenous Knowledge and Archaeoinformatics" and "Modellierung prähistorischen Jagdverhaltens" (Modeling prehistoric hunting) brought together archaeologists and Namibian indigenous Ju/'hoansi San hunting experts for a better understanding of human mobility and behaviour during hunting with traditional means. The study region of the IKai project was the Doro !nawas, a mountainous area in Namibia which is particularly rich in prehistoric Later-Stone-Age (LSA) rock art sites. The rock art mainly depicts engravings of animals and their tracks (Breunig 2018). Being experts in reading animal tracks, Ju/'hoansi San hunters can identify details in prehistoric engravings of animal tracks which are invisible to the nescient (Lenssen-Erz et al. 2021). Hence, large parts of the rock art in the Doro !nawas can be broadly related to knowledge about hunting.

It is generally accepted that past cultures placed rock art with reference to the landscape. When it comes to identify patterns in the spatial distribution of prehistoric rock art sites digital analysis methods such as GIS and (geo-) statistics have become integral parts of methodological toolkit. Here, point-pattern-analysis was used to identify patterns in the spatial distribution of rock art sites. First, the nonparametric Ripley's K test applied to the rock art site locations revealed the presence of spatial clustering at a ca. 400 m distance, which resulted in the presence of four larger site clusters, each comprising > 20 boulders with rock art. Furthermore, the nonparametric rho-hat function revealed a statistically significant relationship between rock art sites and waterholes in a  $\leq 3000$  m distance. However, only one of the three site clusters lies within a  $\leq 3000$  m distance to waterholes. Hence, the presence of three of four rock art site clusters could not be explained by the proximity to water. Since the area at the fringe to the Namib desert is extremely dry and low in vegetation, water sources are extremely important for the survival of humans over longer periods of time.

In the course of the IKai project Ju/'hoansi and Hei//om San did supervised hunts together in the Doro !nawas. No animal was killed during hunting, as final shots were taken with a camera instead of bow and arrow to show hunting potential. San camp location selections, walking trajectories obtained from GPS-Smartwatches as well as decisions made during hunting provided new insights about relationships between landscape and Namibian hunter practices today. Moreover, knowledge about hunting techniques, plant and animal behaviour, and hunting techniques exchanged between group members and with the participating Archaeologists revealed specific explanations about the two types of rock art sites clusters: a)  $\leq 3000$  m to waterholes and b) > 3000 m to waterholes. According to the Indigenous San hunters, these clusters can be explained through different ambush and tracking techniques. Although these explanations are given by hunting practices of indigenous hunter-gatherers today, we argue they provide relevant conclusions about land use patterns by the prehistoric LSA culture in the Doro !nawas due to their profound ecological knowledge.



Fig. 1: Ju/'hoansi San pointing to a rock art site in the Doro Inawas. The depicted art on this wall comprises footprints of various animal species and humans, as well as few animals, lines and dots (Author: Oliver Vogels 2019. Consent was given to publish this photograph by the Ju/'hoansi participant, participants were informed about their data rights).

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## 290. Putting it in Context: Digital tools and open data to support the analysis of Scandinavian rock art

Ashely Green (*Department of Historical Studies, University of Gothenburg*)

Rich Potter (*Department of Historical Studies, University of Gothenburg*)

Christian Horn (*Department of Historical Studies, University of Gothenburg*)

Scandinavia has a wide-ranging landscape of rock art sites, with a growing record of more than 20,000 panels in the Swedish national heritage register alone ("Fornsök," n.d.). As this rock art, including both carvings and paintings, is revisited and documented in high resolution 3D, there is a greater need for digital resources to support both the research and dissemination aspects. Researchers require open data which supports quantitative and qualitative analyses, especially geospatial analysis (Barnett et al., 2024), and stable archiving for publications and long-term data storage. In the case of Scandinavian rock art where carvings are millimetres deep, visualisations and mobile-friendly web resources make the rock art more accessible to the public (Green et al., 2024).

The Swedish Rock Art Research Archives (Svenskt Hällristningsforskningsarkiv, SHFA) has driven the development of workflows for digital documentation and dissemination since it was formed in 2007. Current digital resources include Topography Visualisation Toolbox (TVT, <https://tv.t.dh.gu.se/>) for the visualisation of carvings, GIS tools for the export of AI training data, and an online archive providing open access to rock art documentation (<https://shfa.dh.gu.se/>). TVT is a user-friendly desktop app for the enhanced visualisations of 3D models and point data using a difference map approach (Green et al., 2025). The SHFA online archive, developed in collaboration with the Gothenburg Research Infrastructure in Digital Humanities, provides open access to international rock art documentation, including photos, traditional documentations (e.g., rubbings and tracings), and 3D models. It uses a Postgres database with REST APIs, a Vue frontend for database searching and image viewing, and a 3DHOP-based viewer for

3D models (Westin et al., 2025). Combining these resources, we can enable both multi-method and multi-scalar analyses of rock art.

This talk will focus on Bronze Age rock art in southern Sweden to demonstrate workflows for the visualisation of 3D data, integration of legacy and geospatial data for multi-scalar analysis, and dissemination via the SHFA online archive. Using several panels in Kalleby (Tanum, Västra Götaland) as a case study, we explore the spatial relationships and similarities between motifs in the area. The Kalleby panels include a range of carved motifs, such as anthropomorphs, wagons and animals, and ships, some of which are superimposed. The motifs are recorded using Structure from Motion, and subsequently visualised, interpreted, and vectorised. The use of georeferenced meshes enables us to analyse figures spatially and determine trends between panels in the area and regionally.

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### 372. Secular, totemic, shamanistic? – Testing rock art contexts with ABM and GIS

*Rebecca Döhl (University Münster)*

The task of elucidating the subject of rock art and situating it within its social context is rendered particularly challenging in the absence of contemporary users of this communication form. With the exception of minor instances of tribal markings, this assertion holds largely true when considering the rock art of Egypt and Sudan. Consequently, the spatial approach is the most effective means of deriving meaningful insights into the utilisation of rock art in these regions.

Nevertheless, there are possibilities for the application of concepts from more recent rock art communities and their social embedding and functional context of rock art creation and usage.

The argument proposed by Layton (2000) and Sauvet et al. (2009) for the interpretation of rock art as totemic, secular and shamanistic is an intriguing illustration of the reconstruction of the cultural contexts for rock art through the comparison of their distribution and frequency. Through the analysis of specific animal figures in contemporary rock art traditions, they distinguished three categories: totemic, shamanistic, and secular types of rock art. Drawing on ethnographical and ethnological examples, it was determined that motifs employed in totemic contexts are concentrated in a limited number of locations that hold particular significance within the territory of the respective totemic group. Furthermore, totemic motifs appear in high numbers, but with similar, rather low, frequency, because each clan holds its special totem motif. Shamanistic rock art again exhibits high frequencies of specific motifs, usually those depicting the ‘spirit helper’ of the shaman, while

its distribution is rather equal between all sites. Finally, secular rock art is characterised by a relatively equal frequency of motifs and even distribution at all locations, as they show no special affiliation to specific places. These explanations may also be of interest in relation to other rock art areas. Sauvet et al. (2009) used a generative approach to apply these categories to Upper Palaeolithic rock art which is quite convincing, but might be altered in certain aspects to fit better to the rock art areas of Egypt and Sudan. In view of the absence of robust evidence for totemic and shamanistic practices in Egypt or Sudan, the totemic context may be interpreted in a more general sense as relating to territorial or group-identity-related functions. In a similar manner, the shamanistic rock art can be interpreted as predominantly ritual in nature, occurring within either a social or religious context.

In this presentation, I will propose a methodology for transferring the various methodologies of rock art creation as proposed by Layton (2000) and Sauvet et al. (2009) by using Agent-Based Modelling and Geographic Information System (GIS) approaches. As demonstrated by van Havre in the CAA 2017 with rock art in Brazil, the utilisation of Agent-Based Modelling (ABM) proves to be a fruitful approach for addressing research questions pertaining to the utilisation of rock art, by means of modelling specific behavioural patterns exhibited by rock art creators. The application of the insights provided by Layton(2000) and Sauvet et al. (2009) on agents and their behaviour may facilitate the identification of the most appropriate parameters to be selected for a given context, with regard to frequency or distribution, in other rock art areas. The utilisation of the established conventions inherent within these categories will facilitate the generation of diverse agents that are capable of manifesting the aforementioned behaviours. For the purpose of illustration, rock art from two different regions will be tested: Wadi Berber in Egypt and Wadi Abu Dom in Sudan. The first area encompasses a diminutive region, measuring approximately 1.7 km<sup>2</sup>, which contains a minimum of 60 rock art sites. In contrast, Wadi Abu Dom extends over an area of up to 90 km, comprising numerous rock art clusters.

Given the ubiquity of Python in the field of Geographic Information Systems (GIS) and its compatibility with Agent-Based Models (ABM), such as Mesa Geo, the integration of these two applications is a viable prospect. The data sets of the two research areas created in ArcGIS will be queried through a Python script executed in the Jupiter notebook of ArcGIS and based on MesaGeo, among others. Consequently, a comparison will be made between the statistical means of the model, which incorporates the three cultural contexts, and the actual data from both areas. The integration of ABM and GIS in the modelling of rock art creation behaviour may facilitate the establishment of a comparable foundation for the interpretation of rock art.

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## S18: Connecting the Americas: A Pan-Regional Dialogue among CAA Chapters

*Giacomo Fontana, Texas Tech University, USA (chair)*

*Eduardo Herrera Malatesta, Leiden University, Netherlands (chair)*

*Grégoire van Havre, Universidade Federal do Piau , Brazil (chair)*

*Diego Jimenez Badillo, Instituto Nacional de Antropolog a e Historia, Mexico (chair)*

*Brian Crane, Maryland-National Capital Park and Planning Commission, USA*

**Location:** H rsaal 02

**Session Format:** Other

*The session will be structured as a panel discussion among representatives from different CAA chapters in the Americas. Giacomo Fontana will serve as moderator, with Eduardo Herrera Malatesta representing Latin America and the Caribbean, Diego Jim nez Badillo representing Mexico, Gr goire van Havre representing Brazil, and Brian Crane representing North America. The goal is to facilitate an informal conversation focused on exploring opportunities for collaboration, while also addressing the growing funding and political challenges we all face. Following an initial structured discussion among the panelists, the floor will be opened to the audience for questions and to share their perspectives.*

This panel brings together representatives from the network of CAA regional chapters across the Americas, including CAA North America, CAA Mexico, CAA Brazil, and CAA Latin America & the Caribbean, for an open dialogue on the shared challenges, research interests, and collaborative opportunities that define computational archaeology in the region.

As the global CAA community continues to grow, chapters in the Americas have emerged within diverse socio-political contexts, facing distinct but

often overlapping issues such as uneven access to digital infrastructure and training, linguistic diversity, funding limitations, and the ongoing need to decolonize archaeological knowledge production and digital methods.

While CAA chapters in Europe benefit from longer-established networks and more consistent inter-chapter collaboration, regional coordination in the Americas remains comparatively underdeveloped. This panel seeks to address that gap by fostering dialogue among American chapters and articulating the specific needs and priorities shaped by local conditions, including political instability, institutional fragmentation, and barriers to international cooperation.

The goal of the panel is twofold: first, to explore concrete opportunities for collaboration across American chapters, such as co-organized events, shared resources, and training initiatives, and second, to identify common research priorities that could benefit from sustained cross-regional engagement. These may include digital heritage management, open science practices, spatial and landscape analysis in diverse environments, community-based digital archaeology, and ethical considerations around data sovereignty and representation.

The panel will also reflect on the growing movement of students, researchers, and archaeological projects that cross national borders within the Americas. These transregional academic flows present both challenges and opportunities for building inclusive, context-sensitive approaches to computational archaeology.

By convening this discussion among chapter representatives and the session audience, the panel aims to lay the foundation for sustained inter-chapter collaboration that reflects the diversity, complexity, and potential of archaeological practice in the Americas. It represents both a recognition of ongoing efforts and a step toward a more connected, responsive, and regionally grounded CAA community.



## S20: Digital Archaeological Collections as AI Training Data

*Vera Moitinho de Almeida, University of Porto & INESCC*

*Nevio Dubbini, University of Pisa*

*Aurore Mathys, Royal Museum for Central Africa & University of Liège*

*Gabriele Gattiglia, University of Pisa*

**Location:** Hörsaal 03

**Session Format:** Standard

As the digitisation of archaeological collections accelerates, the field is witnessing a transformative shift in how data are produced, curated, shared, and analysed. Digital databases, archives, and repositories — from site records and objects to high-resolution 3D scans, satellite imagery, and grey literature — are increasingly being enriched and repurposed as training data for artificial intelligence (AI) systems. AI has been applied to a broad range of tasks, such as archaeological sites/objects detection from LiDAR data and aerial photographs, predictive modelling of site locations, automated feature extraction from remote sensing and other data, material provenance analysis, artefact classification, epigraphic transcription, semantic annotation of textual corpora, and data description and integration (Gattiglia 2025). At the core of all these advances lies a foundational component: archaeological training data.

This session explores the multifaceted role of digital archaeological collections as training data for AI, addressing the scientific opportunities, technical and methodological challenges, and social responsibilities that come with applying computational methods to cultural heritage data — issues also tackled by the Managing Artificial Intelligence in Archaeology (MAIA) COST Action CA23141 (2024-2028). Training data will provide novel perspectives for

archaeological research on unprecedented scales. Yet, this shift also raises critical questions about data quality, interoperability, ethics, and sustainability.

Archaeological collections, by their very nature, are rich in contextual, typological, and spatial information, making them attractive for AI applications. However, their integration into computational pipelines requires careful consideration of data quality, standardisation, provenance, and cultural sensitivity. Digital archaeological collections are not neutral or static repositories, but highly heterogeneous and dynamic cultural artefacts shaped by different research traditions, historical collection practices, digitisation strategies, institutional priorities, legal frameworks, and budgetary issues, among others. Crucially, this session does not treat digital archaeological data as a mere technical resource, but as a complex cultural and scholarly artefact in its own right. When repurposed for AI, these collections become part of a complex pipeline of knowledge production — one that demands transparency, critical reflexivity, and inclusive governance.

At the core of our research is a commitment to Open Science, as promoted by the European Commission (2019–), as well as to the FAIR (Wilkinson et al. 2016; *Findable, Accessible, Interoperable, and Reusable*), CARE (GIDA 2018, Carroll et al. 2020; *Collective Benefit, Authority to Control, Responsibility, Ethics*) and TADA (Ivimey-Cook et al. 2025; *Transferable, Accessibility, Documented, Annotated*) data principles. These frameworks are essential not only for encouraging open access to research outputs, collaborative infrastructures, and citizen engagement, but also for fostering reproducible and transparent AI research. They help ensure that archaeological knowledge remains a shared public good, while empowering communities to retain control over their data and benefit from its use.

These principles serve as guiding frameworks for preparing archaeological comparative datasets for AI training in a way that maximizes scientific rigor and minimizes unintended harm. It requires deliberate effort: datasets must

be curated with clear provenance, comprehensive metadata and paradata, and open licensing; data formats must support machine readability and semantic interoperability; repositories must be designed to facilitate long-term accessibility, cross-disciplinary querying, and reuse. Making data reusable entails not only technical compatibility but also rich documentation of context, uncertainty, and cultural sensitivity — factors that are critical in archaeology but often undervalued in AI workflows. Without these foundations, the reuse of archaeological data for AI risks becoming fragmented, opaque, exploitative, or even useless.

This session explores the dynamic intersection of digital archaeological collections and AI, focusing on both the potential and the challenges of using such datasets to train intelligent systems. What constitutes a high-quality training dataset in archaeology, and how do archaeological standards/practices align (or conflict) with AI data requirements? How can the inherent biases in archaeological data (e.g., resulting from archival practices or digitisation strategies) impact the performance and fairness of AI models? In what ways do AI applications risk reproducing or amplifying existing interpretations, narratives, or silences within the archaeological record? What are the emerging best practices for ensuring transparency, reproducibility, and ethical accountability in AI-augmented archaeological research?

Presentations may address a range of themes, including but not limited to:

- Case studies demonstrating the use of AI in archaeological collections;
- Producing and exploring currently openly available (small to large) archaeological benchmark datasets to test AI models;
- Current good practices and guidelines for preparing data files for AI training;
- Preparing, structuring, and curating archaeological datasets for AI training in compliance with Open Science, FAIR, CARE, and/or TADA data principles;

- Limits and problems linked to the creation and/or use of comparative digital collections for AI applications;
- Technical and ethical challenges of bias, representation, and generalization in AI models trained on archaeological data;
- Collaborative efforts and contributions to open, federated data infrastructures and training resources for AI in archaeology.

By bringing together diverse perspectives on the role of digital archaeological collections in AI data training, this session contributes to a broader discussion about the next generation of AI-driven archaeological research and the future of archaeological knowledge production. It encourages critical engagement with the tools and methods we use, while highlighting the possibilities for AI to support archaeological research. The goal is to chart a path forward for guidelines and best practices with ethically grounded, context-aware, and scientifically rigorous applications of AI in archaeology, supported by high-quality data and research practices.

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| <b>15:00 – 15:10</b> | Introduction - <i>The MAIA project and Digital Comparative Collections and AI Training Data for Archaeology</i>                                                                                                     |
| <b>15:10 – 15:30</b> | 453. Experimental AI Applications for Rapid Archaeological Legacy Data Distribution<br><i>John Wallrodt (University of Cincinnati)</i>                                                                              |
| <b>15:30 – 16:00</b> | Coffee break                                                                                                                                                                                                        |
| <b>16:00 – 16:20</b> | 168. Natural Schema Evolution vs Machine Learning Readiness: A Case Study from the Stone-Masters Project<br><i>Maciej Krawczyk (University of Warsaw)</i>                                                           |
| <b>16:20 – 16:40</b> | 79. From Legacy Data to Training Data: AI-Driven and Open Archaeological Workflows: the example of pottery<br><i>Lorenzo Cardarelli (Sapienza University of Rome); Julian Bogdani (Sapienza University of Rome)</i> |
| <b>16:40 – 17:00</b> | 275. Automated Segmentation and Integration of Avifaunal Bone Image Datasets Using Deep Learning-Based Mask Generation                                                                                              |

*Nevio Dubbini (University of Pisa); Gabriele Gattiglia (University of Pisa); Beatrice Demarchi\*; Lisa Yeomans (University of Copenhagen); Marco Pavia\*; Paola Sansone\*; Ramazan Parmaksız\*; Ayşe Ataş Hooglugt (University of Groningen)*

*\*University of Turin*

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| <b>17:00 – 17:20</b> | 99. From Microscopy to AI-assisted Petrography: Preparing Archaeological Thin Sections for Segmentation in TagLab<br><i>Elisabetta di Virgilio*; Giorgio Gosti*; Diego Ronchi*; Marco Callieri*</i> |
|                      | <i>*Consiglio Nazionale delle Ricerche</i>                                                                                                                                                          |

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| <b>17:20 – 17:30</b> | Break                                                                                                                                                                                                                                                                                                                        |
| <b>17:30 – 17:50</b> | 124. Documenting Fragmentary Wall Paintings through AI-Based Segmentation in TagLab. Toward a Standardised Workflow and FAIR Archaeological Datasets<br><i>Caterina Paola Venditti (University of Cassino and Southern Lazio); Diego Ronchi*; Silvia Fortunati (Ministero della Cultura); Giorgio Gosti; Marco Callieri*</i> |
|                      | <i>* Consiglio Nazionale delle Ricerche</i>                                                                                                                                                                                                                                                                                  |
| <b>17:50 – 18:10</b> | 197. Harnessing AI to unlock legacy data: the AutArch experience and beyond<br><i>Maxime Brami (Johannes Gutenberg University Mainz); Kevin Klein (Johannes Gutenberg University Mainz); Felix Riede (Aarhus University)</i>                                                                                                 |

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|--------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>18:10 –<br/>18:30</b> | 337. Generative Modeling for Potteries: A GMM-GAN Based Framework for Completion and Clustering of Pottery Fragments<br><i>Suhui Liu (University of Science and Technology Beijing)</i>                                                                                     |
| <b>18:30 –<br/>18:50</b> | 202 – From Pots to Points and Back Again: A 3D Scanning and Generative Machine Learning Workflow for Pottery Studies<br><i>Dries Daems (VU Amsterdam); Jitte Waagen*; Mason Scholte*; Mikko Kriek</i><br><br><i>* Universiteit van Amsterdam</i>                            |
| <b>18:50 –<br/>19:10</b> | 45. Carian pottery geographical differentiation using meta-learning, transfer learning, and signal processing based neural network hybrid architectures<br><i>Deniz Kayikci (Universitat Autònoma de Barcelona); Juan Anton Barcelo (Universitat Autònoma de Barcelona)</i> |
| <b>19:10 –<br/>19:30</b> | Discussion                                                                                                                                                                                                                                                                  |

## 45. Carian pottery geographical differentiation using meta-learning, transfer learning, and signal processing based neural network hybrid architectures

*Deniz Kayikci (Universitat Autònoma de Barcelona)*

*Juan Anton Barcelo (Universitat Autònoma de Barcelona)*

The study of ancient pottery provides valuable insights into the cultural, economic, and technological exchanges of past civilizations. Protogeometric and geometric period pottery originating from Attica emerged in the Early Iron Age (EIA 1200-800 BC), at the beginning of the 1st millennium BC, and is found in different geographical regions. Although largely similar, they sometimes exhibit stylistic and technical nuances. The Carians lived in small communities, some within or near Greek cities on the coast (Halicarnassos, Iasos, Miletus, Melia...etc) and others in their own inland settlements; even there they became sufficiently impressed to manufacture their own style of Late Geometric pottery, under Dodecanesian influence (Cook and Dupond, 198; Coldstream, 2004).

Early Iron Age pottery found in the Caria Region, the ancient name for the southwestern coast of Anatolia, requires investigation using new and modern techniques, as it is not yet known style differences locally. Traditional archaeological methods used to classify and analyze these artifacts are often based on subjective visual assessments and manual comparisons, which can be time-consuming and lead to differences among observers (Adams and Adams 1991; Rowlands and Spriggs, 1998; Barcelo 2010; Barcelo 2022; Bellat, 2025). This article presents a new approach to the analysis of Carian pottery, utilizing neural networks and meta-learning techniques with signal processing to identify and measure geographical differences in ceramic production.

We present a dataset of Carian pottery fragments collected from important archaeological sites in the Caria Region and seized from smuggling activities, presented with detailed descriptions of their morphological and decorative

features (Bulba, 2005). Using high-resolution images, we extract distinctive features from pottery fragments by focusing on shape, surface treatment, and decorative motifs using convolutional neural networks (CNN). To address the common problem of limited and imbalanced data in archaeological studies, we improve classification performance across diverse and underrepresented sites by applying meta-learning algorithms, specifically few-shot learning and model-agnostic meta-learning (MAML) algorithms. Meta-learning, or "learning to learn" focuses on improving the learning process itself, enabling models to quickly adapt to new tasks with minimal data. It includes Few-Shot Learning (FSL) and a part of Auto-ML methodologies (Vanschoren, 2018; Hospedales et al., 2021). Although these approaches benefit from substantial domain knowledge, they encounter significant limitations due to the pronounced intra-class variability of artifacts and the often subtle inter-class distinctions. Traditional computer vision methods based on handcrafted features are inadequate in capturing the intricate textures and repetitive geometric patterns characteristic of artifact typologies. While more recent deep learning models have demonstrated potential, their effectiveness has been constrained by the limited availability of labeled datasets for ancient materials. Moreover, most existing learning frameworks have failed to exploit frequency-domain representations, which are essential for analyzing recurring decorative motifs. In the present study, a novel deep learning framework was implemented for the classification of potteries according to geographical origins. The initial feature extraction phase employed signal processing techniques to capture primary attributes such as edges and curves (Wang and Zlu, 2024). Comparative evaluations were conducted to assess model performance, and the results revealed a notable increase in classification accuracy, particularly in distinguishing visually similar specimens. These findings validate the proposed method's efficacy for small-sample archaeological datasets.

Digital signal processing (DSP) encompasses the analysis, transformation, and manipulation of signals through mathematical operations, distinguishing it from data rearrangement tasks in general-purpose computing by leveraging specialized microprocessors optimized for algorithms such as digital

filtering and Fourier analysis (Smith, Ch. 28). Unlike traditional microprocessors like the Pentium, which prioritize data manipulation involving movement and inequality testing, DSP architectures emphasize multiplication and addition-intensive computations, as exemplified by finite impulse response (FIR) filters where output samples are derived from convolving input signals with kernel coefficients (Smith, Ch. 28). Over the past decade, DSP has proliferated across applications from cellular telephony to scientific instrumentation, with research groups integrating algorithmic innovation and practical deployment in domains including speech, image, video, and geophysical processing (Oppenheim et al., 1984). This synergy extends to knowledge-based paradigms, such as symbolic correlation for efficient speech vector matching and reconstruction from distorted zero-crossings or multi-threshold data, while adaptive filtering techniques address noise cancellation and parametric modeling in dynamic environments (Oppenheim et al., 1984; Stearns, Ch. 5). Collectively, these advancements underscore DSP's evolution toward hybrid numerical-symbolic frameworks, bridging theoretical rigor with implementation efficiency on VLSI-enabled architectures.

The integration of classical signal processing techniques with deep learning architectures offers significant advantages, particularly for archaeological datasets characterized by noise, sparsity, and structural irregularities. By extracting meaningful time-frequency and spatial features before model training, these hybrid frameworks enhance interpretability and reduce overfitting risk in small-sample scenarios. Signal processing provides more compact and informative data representations, enabling deep networks to focus on high-level semantic patterns rather than redundant pixel-level variations.

The implementation of nested cross-validation represents a crucial methodological component that ensures unbiased performance estimation while enabling systematic hyperparameter optimization (Vabalas et al., 2019). This approach is particularly important for archaeological applications where limited data makes robust evaluation challenging and where standard machine learning validation approaches may not provide reliable performance estimates for small sample sizes.

The integration of signal processing based neural networks models consisting transfer learning and meta-learning not only advances the methodological toolkit for archaeological research but also sheds new light on the geographical distribution and stylistic evolution of Carian pottery. By revealing previously unrecognized patterns of similarity and divergence, our approach contributes to a deeper understanding of ancient trade networks, craft specialization, and cultural identity in the Carian world. This interdisciplinary study bridges the gap between computer science and archaeology, demonstrating the potential of artificial intelligence to transform the analysis of material culture and historical connectivity. Furthermore, signal processing based hybrid approaches significantly enhance the model's ability to generalize to unseen sites, offering a robust framework for identifying provenance and tracing cultural interactions. Even if limited-sampled dataset.

**Keywords:** Carian pottery, neural networks, meta-learning, archaeological classification, signal processing, few-shot learning, cultural heritage, provenance analysis

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## 79. From Legacy Data to Training Data: AI-Driven and Open Archaeological Workflows: the example of pottery

*Lorenzo Cardarelli (Sapienza University of Rome)*

*Julian Bogdani (Sapienza University of Rome)*

Ceramic materials are considered to be among the most fundamental sources of archaeological knowledge, as they provide key information about chronology, function, technology, and cultural interactions (Hunt 2019). However, the study of ceramics remains an arduous process, entailing numerous manual stages—from cleaning and drawing to classification and publication. This fact has had a significant impact on the percentage of items published compared to those excavated. Moreover, this fact has had a considerable impact on the percentage of items published in comparison to those excavated. Moreover, a significant proportion of valuable ceramic information remains confined within legacy data sources, including printed catalogues, excavation reports, unpublished archives, and drawings. These materials are seldom digitised or standardised into machine-readable formats, hindering effective access and utilisation. In parallel with this, archaeology has undergone a transformative shift towards computational approaches and the large-scale use of artificial intelligence (AI) and machine learning (ML) systems for over a decade (Gattiglia 2025). These technologies are increasingly reliant on digital archaeological collections as a source of training data. However, the integration of ceramic datasets into AI workflows gives rise to significant methodological and theoretical challenges in terms of data quality, interoperability, standardisation, and semantic consistency. The critical question is not simply whether AI *can* be applied to the documentation and analysis processes of archaeological ceramics, but *how* legacy documentation can be transformed into high-quality, ethically curated datasets that preserve archaeological context while enabling computational analysis. This contribution presents an open-source and open-weights modular framework designed to transform raw and diverse ceramic documentation into structured, reusable, and interoperable data suitable both for classical

archaeological analysis and data-driven research. The still under active development framework already provides a reproducible computational environment for processing and analysing ceramic corpora. Its workflow is organised into three main stages: **1) Digitisation and Preprocessing of Legacy Data.** Using a combination of computer vision models such as YOLO and the Segment Anything Model (SAM), the framework automates the extraction of ceramic profile drawings from both unpublished archaeological documentation (drawings table) and published materials (PDFs). This process converts static 2D illustrations into structured digital representations enriched with metadata, including contextual information, dimensional data, and other descriptions where available. The automated detection pipeline significantly reduces processing time up to 20x compared to manual methods. **2) Inking, Semantic Enrichment, and Vectorisation.** Raw drawings are processed through an automated inking pipeline that standardises line weights and visual conventions, making them publication ready. The extracted data are then transformed into semantic vector representations that integrate morphological components of each vessel—profile, decorations, handles—as discrete, machine-readable entities. This semantic segmentation ensures postprocessing and interoperability across different archaeological databases and repositories, allowing comparative analysis at the component level rather than treating each vessel as a raster indivisible unit. **3) Similarity Analysis.** Through ML algorithms, including unsupervised clustering and metric learning approaches, a specific module identifies morphological similarities and functional patterns within and across collections. The framework employs both unsupervised contrastive learning to discover latent typological structures and supervised methods that incorporate archaeological domain knowledge through expert feedback. These methods facilitate the creation of new typological groupings based on quantifiable morphological features, while highlighting previously unnoticed relationships between large ceramic assemblages from different contexts or periods. Furthermore, this approach allows for a theoretical comparison with the traditional classification of ceramics, offering new information and reflections on the concepts of ‘similarity’ and ‘typology,’ which are widely used in the study of ceramics and

material culture. Importantly, this process transforms digitised ceramic data into high-quality training datasets that can be reused for future AI research in archaeology.

The framework, currently under development at LAD (Laboratorio di Archeologia Digitale) at Sapienza University of Rome which has been tested on 1) Raw archaeological drawings from different excavations of the Sapienza University 2) Published ceramic catalogues from monographs and articles. 3) Standardised ceramic profiles from the AIPPA, a comprehensive dataset for quantitative analysis (Cardarelli 2024). The findings illustrate the efficacy of the computational pipeline in reducing the time required for the publication process, enhancing the layout, and ensuring a data-driven approach to material analysis at the analytical level. More significantly, the ML-based similarity analysis enables quantitative comparison across large ceramic assemblages, revealing morphological patterns and relationships that would be difficult to identify through traditional autoptic analysis. This data-driven methodology provides archaeologists with computational tools that complement traditional typological expertise, operating at scales and with levels of consistency that enhance the interpretative process without replacing human judgment. All components of the framework will be released as open-source software under permissive licensing, and the project encourages transparent data workflows through public documentation of preprocessing steps, model parameters, and uncertainty levels. Each stage of the pipeline is designed to be inspectable and reproducible, allowing other researchers to adapt the framework to their own ceramic assemblages or to critically evaluate the computational methods employed.

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## 99. From Microscopy to AI-assisted Petrography: Preparing Archaeological Thin Sections for Segmentation in TagLab

*Elisabetta di Virgilio (Consiglio Nazionale delle Ricerche)*

*Giorgio Gosti (Consiglio Nazionale delle Ricerche)*

*Diego Ronchi (Consiglio Nazionale delle Ricerche)*

*Marco Callieri (Consiglio Nazionale delle Ricerche)*

Introduction. The integration of artificial intelligence (AI) into archaeological research is transforming traditional analytical workflows, enabling more systematic, reproducible, and large-scale interpretations of complex visual datasets. Among the various fields affected by this technological revolution, ceramic petrography stands out as one of the most promising areas for innovation. Petrographic analysis of thin sections is a pillar of archaeometric investigation, offering insight into the provenance, technological choices, and production processes of ceramic materials. However, traditional examination of thin sections under polarized light remains a highly specialized, time-consuming, and inherently subjective task, reliant on expert knowledge and visual interpretation. The development of image-based analytical pipelines supported by AI thus represents a critical step toward automating and standardizing the identification of mineral inclusions, matrix composition, and porosity in archaeological ceramics.

In recent years, advances in digital image analysis have begun to address some of the core limitations of conventional petrography. Image analysis techniques applied to microphotographs have allowed quantitative characterization of ceramic fabrics, providing numerical data about the shape, size, and orientation of inclusions and pores (Park et al. 2019, 75-85). At the same

time, methods from geosciences have proven effective in automating rock classification through deep learning, where convolutional neural networks (CNNs) trained on plane-polarized (PPL) and cross-polarized (XPL) images achieve classification accuracies exceeding 85% (Su et al. 2020, 1477-1484). Yet, despite such progress in geosciences, the adaptation of these models to archaeological ceramics remains limited, and there is the necessity of establishing standardized protocols to transform raw petrographic images into training-ready data. Our work focuses on developing a reproducible workflow for the preparation and pre-processing of microphotographs of ceramic thin sections, intended for future use in deep-learning models for automatic mineral classification. The study is grounded in ongoing experimentation using TagLab, an open-source AI-powered segmentation software developed by the Visual Computing Lab of CNR-ISTI (Pavoni et al. 2022, 1-17). Originally created for marine ecological imaging, TagLab provides a user-friendly environment for manual and semi-automatic annotation of raster images. Its flexibility, open architecture, and integration of assisted segmentation tools make it particularly suitable for adapting to the microscale challenges of ceramic petrography.

**Methods and Materials.** The experimental dataset consisted of high-resolution microphotographs of archaeological ceramic thin sections acquired under both plane-polarized (PPL) and cross-polarized (XPL) light using a Leica Laborlux 12 POL microscope equipped with a Zeiss Axiocam 105 color camera. Images were captured at 2.5× optical magnification with a spatial resolution of approximately 483 pixels per millimeter, yielding files of 2592 × 1944 pixels. Each sample was documented twice, in PPL and XPL, to capture complementary optical properties (PPL usually shows the shape, color and cleavage of minerals, while XPL reveals extinction and interference patterns). Before annotation, a dedicated pre-processing phase was implemented to standardize illumination and make the PPL and XPL images stackable. Basic corrections were performed using ImageJ/Fiji to normalize lighting, remove noise, and align the images through sub-pixel registration. The aligned images were subsequently fused into a single composite image (CI) using

Principal Component Analysis (PCA) (fig. 1). This step allowed the combination of textural and optical information into a synthetic false-color image, essential for the next phase.

Following image preparation, segmentation and annotation is being performed in TagLab through a combination of manual and AI-assisted tools, after defining a specific annotation dictionary. For the annotation process, different segmentation tools are employed according to the complexity of the image. Each region is associated with a label within a dedicated dictionary and then exported as multiple outputs.

**Results.** The results demonstrate that segmentation accuracy varies according to texture. Coarse ware samples, characterized by more distinct inclusions and sharper boundaries, generate the most reliable annotations. Fine ware samples, in contrast, present more ambiguous transitions between matrix and pores, requiring additional manual correction. The combination of PCA-fused imagery and TagLab's assisted segmentation tools has substantially reduced the time required for annotation compared to conventional manual tracing, while maintaining a high degree of precision.

The annotated outputs can be exported as both binary masks and structured metadata tables containing geometric and spatial descriptors (area, perimeter, roundness/roughness, and elongation). These quantitative attributes enable the generation of histograms and distribution plots describing the proportion, density, and alignment of inclusions and pores within each sample, and they provide a foundation for future statistical analyses.

TagLab's hybrid architecture proved particularly advantageous. It allowed non-expert users to produce high-quality annotations without prior knowledge of machine learning, while maintaining compatibility with deep-learning frameworks through standard export formats (GeoTIFF, JSON, CSV). Moreover, the platform supports the entire annotation lifecycle, from dataset creation to model validation.

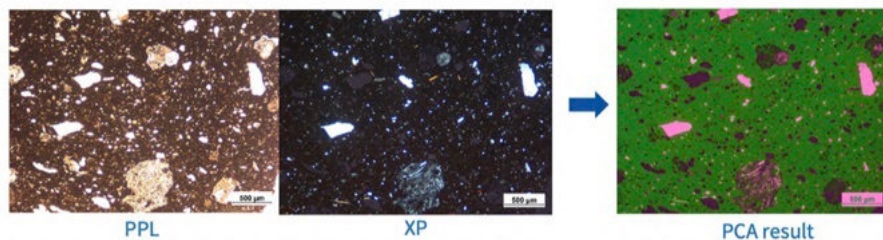


Fig. 1 – PCA-fused imagery process

Discussion. The ongoing experiments highlight several methodological implications. First, the adaptation of TagLab to microscopic imagery demonstrates the feasibility of bridging macro- and microscale image analysis within a unified open-source framework.

Second, the pre-processing pipeline, especially the registration and PCA fusion of PPL/XPL pairs, represents a reproducible and efficient solution for overcoming illumination inconsistencies caused by mineral birefringence.

Third, the pixel-level annotations will lead to the creation of an open and reusable dataset of ceramic thin sections, structured according to FAIR data principles. Such datasets are essential to ensure transparency and comparability in AI-driven archaeological research, allowing models trained in one context to be validated or fine-tuned across others.

Future work will focus on expanding the dataset to include a wider variety of ceramic fabrics, magnifications, lighting conditions, and on validating neural networks for fully automatic segmentation of petrographic images.

Beyond technical results, the broader significance of this work lies in the gradual transition from manual petrography to AI-assisted petrography, in which annotated imagery becomes a reusable resource for machine learning. The creation of a standardized, high-resolution dataset of ceramic thin sections will not only facilitate the training of neural networks for automatic mineral and texture classification but also promote interoperability with other digital collections in archaeology and heritage science.

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## 124. Documenting Fragmentary Wall Paintings through AI-Based Segmentation in Taglab. Toward a Standardised Workflow and FAIR Archaeological Datasets

*Caterina Paola Venditti (University of Cassino and Southern Lazio)*

*Diego Ronchi (Consiglio Nazionale delle Ricerche)*

*Silvia Fortunati (Ministero della Cultura); Giorgio Gosti*

*Marco Callieri (Consiglio Nazionale delle Ricerche)*

## Introduction

Beyond their stylistic and iconographic value, painted plasters contain a wealth of information that can shed light on building practices, economic organisation, and patterns of reuse. Their preservation is often partial and dispersed: the vast majority of surviving examples originate from collapsed contexts, secondary deposits, or restoration waste, resulting in large and highly

heterogeneous assemblages. Consequently, their documentation and analysis are typically time-consuming, heavily reliant on manual processes, and rarely standardised.

Recent advances in digital recording are changing how archaeologists approach material evidence, transforming images into analytical resources. However, the integration of these data within artificial intelligence workflows remains gradual and uneven – a promising but still incomplete transition. The archaeological field continues to face significant challenges in adapting its heterogeneous, context-rich data to the technical standards required by machine learning. These challenges are particularly evident when dealing with materials that are inherently fragmentary, multilayered, and morphologically complex: Roman wall paintings are emblematic of this condition.

## Materials and Methods

This study builds on ongoing experimentation with AI-driven segmentation of fragmentary Roman paintings from the site of Castrum Inui (Ardea, central Italy). These materials, dated to the second half of the 2nd century AD, were recovered as a primary deposit within a building collapse – a context that preserves the spatial association of fragments but requires complex post-excavation documentation. Each fragment was photographed and processed through photogrammetry to produce orthophotos with a ground sampling distance of 1 mm/px, balancing the need for accurate colour and contour recognition with manageable data size for computational processing.

The study uses TagLab as the main environment for image segmentation and annotation. Within TagLab, various assisted segmentation tools address the main documentation needs of fragmentary wall paintings: primarily isolating individual fragments from composite orthophotos and distinguishing decorated surfaces from plaster losses, as well as attempting to identify preparatory or construction traces, separate figures from backgrounds, and detect distinct colour areas within the same decorative field.

## Results

The dataset developed for this study currently consists of 40 high-resolution orthophotos of painted plaster fragments. These images form the core of a benchmark dataset intended for testing and refining segmentation models in archaeological contexts. To enhance model robustness and compensate for the limited number of original samples, a systematic data augmentation process has been applied, including geometric transformations, rotations, mirroring, colour balancing, brightness variation, and synthetic noise generation. This approach aims to replicate the natural variability of fragmentary surfaces, such as erosion, pigment fading, or partial loss, while maintaining controlled conditions for evaluation and reproducibility.

The dataset is curated according to FAIR and CARE principles, with explicit documentation of provenance, acquisition parameters, and post-processing steps. Each image is accompanied by detailed metadata (context of recovery, scale, illumination setup, camera calibration) and paradata describing both manual and AI-assisted operations. The resulting repository serves as both a documentation resource and a reference dataset for future machine-learning experiments in heritage segmentation.

Each segmentation output has been validated through visual inspection and cross-checked against manual tracing. The resulting masks and labels, exported in vector (SVG/GeoJSON) and raster formats, will ensure compatibility with broader digital archives. Metadata describing the acquisition context, lighting, calibration, and processing parameters have been recorded to guarantee transparency and reproducibility.

## Discussion

The earlier phase of the project, conducted using the open-source platform TagLab, showed that interactive segmentation techniques could significantly reduce the time needed to isolate individual fragments and their decorated surfaces. In previous experiments, AI-assisted segmentation reduced manual processing time by approximately 70% for fragment isolation, while maintaining contour precision sufficient for metric documentation and morphological comparison. More complex tasks explored during these initial tests, such as detecting preparatory traces or distinguishing multiple colour zones

within figures, still required user intervention and fine-tuning. In these cases, downsampling improved segmentation performance, suggesting that feature recognition at coarser scales may compensate for local irregularities and micro-erosion. Despite these limitations, the first experiments demonstrated consistent repeatability and robustness across different fragments, paving the way for larger-scale, semi-automated documentation workflows. Building on these preliminary results, the application of AI-based segmentation tools can provide a more decisive methodological advance. Unlike traditional manual vectorisation or classical threshold-based segmentation methods, modern neural network approaches can distinguish subtle variations in texture, colour, and morphology, enabling automated delineation of decorated surfaces and preparatory traces. By combining visual recognition and machine learning, these approaches offer new possibilities for producing structured, comparable, and reusable archaeological datasets. Such datasets not only accelerate documentation but also lay the groundwork for future AI applications, aligning with FAIR and Open Science principles.

AI segmentation is not merely a tool for analysis but a driver for redefining documentation protocols towards reproducible and interoperable digital datasets. For this reason, careful dataset curation is a key prerequisite for reliable and reproducible AI-assisted documentation. As variations in colour calibration, illumination, and image compression can significantly affect segmentation accuracy and generalisation, establishing uniform acquisition and post-processing standards is essential for model training consistency.

The project contributes to creating benchmark-quality image datasets for cultural heritage AI applications, ensuring openness, traceability, and contextual accountability in line with the CARE principles. Given the recent European AI Act (2024) the project adopts a responsible and transparent approach to artificial intelligence. Enriched data are clearly marked as synthetic derivatives to prevent confusion between documentation and training material.

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## 168. Natural Schema Evolution vs Machine Learning Readiness: A Case Study from the Stone-Masters Project

*Maciej Krawczyk (University of Warsaw)*

### Introduction

Digital datasets in archaeology are increasingly conceived not just as archives of information but as resources intended for computational reuse, including potential applications of machine learning. These databases often adopt relational schemas, controlled vocabularies, and metadata standards intended to support future interoperability and algorithmic analysis. Yet, as projects progress, such systems rarely remain static. New research questions, changing personnel, software updates, and interpretive revisions drive continuous modification of data structures and terminologies. This phenomenon—here termed natural schema evolution—is an intrinsic part of humanities research, reflecting its interpretive and iterative character.



However, while this flexibility enhances scholarly value, it often undermines the dataset's machine learning readiness. Even minor schema or annotation changes can introduce inconsistencies, unbalanced class distributions, and undocumented transformations that reduce the dataset's usability for computational modelling and long-term reproducibility. In many digital archaeology projects, the data's suitability for ML therefore degrades over time, despite the initial intention to keep it "AI-ready."

This presentation examines this phenomenon through the case of the Stone-Masters Project at the University of Warsaw, which investigates Late Antique stonecutters' workshops and epigraphic practices. The project's relational database was designed from the outset with computational reuse in mind, yet its ongoing evolution has raised questions about how to balance interpretive flexibility with data stability. By tracing the history of the database's development and assessing how schema changes influence model performance, the study explores the broader issue of how digital humanities data gradually lose their machine learning readiness. It also considers strategies to manage this process more effectively through documentation, versioning, and stewardship practices that acknowledge evolution as a normal feature of scientific work in the humanities.

#### Methods and Materials

The study is based on the ongoing development of the Stone-Masters Project database, which documents stonecutters' workshops, inscriptions, and provenance data from Late Antiquity. The project provides an ideal testbed for observing how data structures evolve naturally within a research context that aims to remain compatible with computational analysis. Rather than presenting completed experiments, this work outlines a methodological framework for assessing and mitigating the degradation of machine learning readiness over time.

The research begins with a qualitative analysis of the database's history and evolution. Successive versions of the schema, from the project's initial design to its current working form, are being reviewed to identify patterns of change in structure, terminology, and metadata completeness. This examination draws on project documentation, team discussions, and recorded curatorial

decisions to understand why specific schema changes occurred and what effects they may have on data consistency.

In parallel, the project will examine how these structural and semantic shifts affect the feasibility of applying machine learning. Rather than building full predictive models, the work will concentrate on pinpointing where inconsistencies, missing data, or changing vocabularies begin to disrupt automated processing. The outcome will be a set of preliminary indicators for assessing data stability and a proposal for simple auditing routines that could become part of regular project maintenance.

Ultimately, the goal is to develop a methodology that can be applied not only to Stone-Masters but to other humanities databases that experience similar patterns of natural evolution. The emphasis is on establishing a clear conceptual framework and practical monitoring steps, rather than on delivering final quantitative results at this stage.

#### Results

Although the study is still in progress, several preliminary observations have already emerged from the review of the Stone-Masters database and its development history. The first is that schema evolution in this context is not random but reflects the natural rhythm of archaeological research. Each phase of work—whether prompted by new field data, changing research questions, or collaboration with external specialists—introduces modifications that make sense from a scholarly perspective but can quietly undermine structural consistency.

Early examination of the database versions suggests a gradual increase in complexity: new tables and relationships have been added, controlled vocabularies refined, and certain classifications re-interpreted. These changes have improved the expressiveness of the data but have also created minor incompatibilities between versions, particularly in how workshops and inscription attributes are described. This illustrates how the same processes that enhance human interpretability can reduce computational predictability.

The emerging result, therefore, is conceptual rather than statistical: the evolution of archaeological databases is an inevitable and valuable process, but

without deliberate documentation and governance, this evolution diminishes the dataset's practical usefulness for reproducible computational research.

#### Discussion

The experience of the Stone-Masters Project illustrates a recurring challenge in digital archaeology: balancing interpretive flexibility with the structural stability required for computational use. As the project's database evolves, new categories and attributes are regularly introduced to capture finer distinctions and integrate additional evidence. While this expansion enhances the interpretive richness of the record, it also increases the number of fields far more rapidly than the number of recorded artefacts. The result is growing sparsity and a form of the curse of dimensionality, where more descriptive features make the dataset less suitable for reliable machine learning.

This situation reveals that natural schema evolution is not a technical flaw but an inherent characteristic of long-term archaeological research. From a computational perspective, however, uncontrolled schema growth gradually reduces model stability and reproducibility. Addressing this does not mean limiting interpretive development but documenting and managing it. Simple practices such as schema versioning, lightweight changelogs, and periodic checks for feature inflation can help maintain a balance between conceptual expressiveness and analytical usability.

These reflections are a secondary but valuable outcome of the broader Stone-Masters Project, whose primary goals remain archaeological and historical. Yet the project's evolving data infrastructure provides an opportunity to observe how humanistic and computational logics intersect. Recognizing data evolution as an ongoing process rather than a one-time design problem may help digital archaeology sustain both interpretive openness and long-term machine learning readiness.

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## 197. Harnessing AI to unlock legacy data: the AutArch experience and beyond

*Maxime Bami (Johannes Gutenberg University Mainz)*

*Kevin Klein (Johannes Gutenberg University Mainz)*

*Felix Riede (Aarhus University)*

Extracting archaeological data from published catalogues is traditionally a time-consuming, repetitive, and error-prone task. The AI-assisted workflow 'AutArch' has been developed to generate uniform archaeological datasets from heterogeneous published legacy resources (Klein et al. 2025). AutArch provides a reproducible and transferable methodology that leverages AI to speed up, automate, and standardise the extraction of information from legacy resources such as archaeological illustrations and photographs. The workflow ensures that resulting datasets remain consistent and fully comparable, across different languages, alphabets, and drawing conventions. The graphical interface of the software allows manual expert validation.

AutArch was originally designed to extract burial data from archaeological catalogues, capturing features such as the shape, size and orientation of 3rd millennium BC graves. We here reflect on the potential for AutArch to become scalable and applicable to a wider range of objects, also outside of archaeology. We demonstrate how this new data collection method can be applied to the study of ceramic form and decorations, or integrated with existing workflows like OutlineR (Matzig et al. 2021) to systematically analyze artefact types such as published stone points. By deploying AutArch on images of exceptional Chalcolithic arrowheads from Montelirio, Spain, we show that the extracted shapes reflect the entire chaîne opératoire, from blanks to finished artefacts.

We present improved workflows for the systematic extraction of both attribute data and geometric morphometric information from archaeological

catalogues, with a focus on two categories of objects: burials and artefacts. AutArch now accommodates complex and broken shapes, ensuring scalability. Benchmarking tests show that the AutArch workflow is not only substantially faster than manual data collection but also more reliable, reducing human error and ensuring reproducibility across datasets.

AutArch is now recognized as an official use case by the COST Action MAIA, “Managing Artificial Intelligence in Archaeology”. Beyond its practical applications, this paper addresses several practical, ethical, and legal considerations associated with the use of AI for extract information from archaeological illustrations, such as copyright-related issues and the potential automation of repetitive jobs such as database entry and curation.

The AutArch initiative actively supports FAIR (Findable, Accessible, Interoperable, Reusable) principles. A docker configuration is available for download from Zenodo (<https://zenodo.org/records/15369892>), and the source code is accessible on GitHub (<https://github.com/kevin-klein/AutArch>).

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## 202. From Pots to Points and Back Again: A 3D Scanning and Generative Machine Learning Workflow for Pottery Studies

*Dries Daems (VU Amsterdam)*

*Jitte Waagen (Universiteit van Amsterdam)*

*Mason Scholte (Universiteit van Amsterdam)*

*Mikko Kriek*

### Background

Pottery studies are the bread and butter of archaeological projects in many parts of the world, especially in the Mediterranean and Near East. Due to their abundance, ceramics can provide critical insights into the social life of past societies, economic organization and production, cultural practices, and more. Recent digital and computational advances are opening up new windows to enhance our understanding of the past through this important material category. The advent of 3D scanning technology offers the potential for precise, reproducible data capture, while machine learning algorithms can process these datasets to reveal detailed data patterns previously unattainable.

In recent years, Reflectance Transformation Imaging (RTI), photogrammetry, and structured light/laser scanning have emerged as powerful solutions for realistically capturing three-dimensional information of pottery. Imaging techniques such as these are usually applied as part of the documentation procedure, whereas the analytical component is often missing or lacking. In this project, we aim to address this gap by developing a state-of-the-art integration of 3D scanning technologies and generative machine learning models.

### Research Aims

The project aims to create a comprehensive approach and workflow that has the potential to transform ceramic analysis. Through 3D scanning, we create

high-resolution input datasets for machine learning algorithms that will generate similarity networks to enhance classification accuracy, improve chronologies, and deepen our understanding of production techniques, and usage of these materials.

The resultant pipeline does not seek to make the material specialist redundant – a worry often expressed by specialists faced with these new technologies – but rather to enhance the processing capabilities of the specialist in the face of high-dimensional data.

#### Methods

In this project, we opt for structured light scanning - using the projection of light patterns to create high-resolution 3D models – as it is particularly useful for studying vessel morphology and detecting surface details for detailed analysis of surface decoration, and manufacturing techniques.

The generative ML component consists of using pretrained 3D deep learning models (e.g. PointNet++, DGCNN, and Point-BERT) as feature extractors at inference time. In particular, self-supervised and generative-style models provide latent shape representations that encode global and local geometric properties of pottery material, without requiring task-specific training on the limited dataset.

The extracted latent representations are evaluated through unsupervised clustering and similarity analysis, using metrics such as intra-/inter-cluster distances. Results are further assessed by comparing clusters against expert-driven morphological or typological groupings and by examining whether the embeddings support meaningful differentiation between data points. The expected outcome is that pretrained 3D representations enable robust clustering and interpretability despite small sample sizes.

#### Expected Results

The developed methodology is tested on a case study of Hellenistic pottery from a number of sites in Türkiye, including most notably Türkmen-Karahöyük (Central Anatolia) where the outlined workflow was first and most extensively tested and applied. This site has yielded material in

extraordinary amounts and quality, providing the ideal basis for a groundbreaking contribution to (Hellenistic) pottery studies. By making the methodological pipeline – and eventually the resultant datasets and outcomes – openly available, the project will fully adhere to prevalent best practices in open science, while also generating the potential to contribute to the advancement of object analysis within and beyond archaeology.

## 275. Automated Segmentation and Integration of Avifaunal Bone Image Datasets Using Deep Learning-Based Mask Generation

*Nevio Dubbini (University of Pisa)*

*Gabriele Gattiglia (University of Pisa)*

*Beatrice Demarchi (University of Turin)*

*Lisa Yeomans (University of Copenhagen)*

*Marco Pavia (University of Turin)*

*Paola Sansone (University of Turin)*

*Ramazan Parmaksız (University of Turin)*

*Ayşe Ataş Hooglugt (University of Groningen)*

#### INTRODUCTION

Human-bird relationships play a significant role in past ecosystems, subsistence strategies, and cultural world-making. AviArch (<https://archaeobiomics.com/aviarch-avifauna-in-archaeoecological-networks/>) is an ERC-Consolidator Grant project investigating the long-term interaction between humans, birds and the environment, by combining classic zooarchaeological methods, biomolecular approaches, AI-based classification of avian remains, and community/ecology modelling. Within this framework, the present contribution addresses a significant challenge: how to preprocess and harmonise heterogeneous digital image datasets of avifaunal skeletal remains, so

that they can be compared and quantitatively analysed across collections, and support AI-driven analysis.

## MATERIALS AND METHODS

### Dataset and Scope

The data consist of digital photographs of avian skeletal elements (bird bones), organised into three collections. Each collection has different setups, imaging protocols and measurement devices. The first collection includes about 1800 photographs of 5 skeletal elements from 25 duck species (Haruda et al., 2024) and 5 non-anatid taxa. Most specimens originate from the Zoological Museum of Copenhagen and the Natural History Museum, Tring, photographed under controlled conditions. The second collection includes about 7500 images across 12 families, 19 species, and 41 individuals, captured under 24 lighting, viewpoint, device and resolution conditions. It reflects species commonly found in Eurasian archaeological assemblages, with an emphasis on Anatidae. The third collection, collected by Zooarchaeology specialists at the University of Groningen, adds about 1670 photographs of nine skeletal elements, taken under diverse setups. The scope of this work is to provide a harmonised, taxonomically diverse image repository that enables the development of AI-based classification models and subsequent ecological network analyses within the AviArch framework.

### Segmentation Model

The preprocessing pipeline is designed to ingest a root directory of images, traverse subfolders, preserving the original folder structure to retain provenance metadata, and output a parallel directory of segmented bone images. We employ the recent transformer-based model Segment Anything Model (SAM, version 1.0) developed by Meta AI (Kravtsov et al., 2023). Before segmentation, all photographs undergo a standardised pre-processing phase to reduce inter-collection variability in visual appearance. After the model is loaded, an automatic mask generator (SamAutomaticMaskGenerator) is used to produce candidate object masks for each input image. The selection

of model size and checkpoint balances segmentation accuracy with computational feasibility on the available GPUs and CPUs.

The code was written in Python (version 3.11.9) using torch, numpy, opencv-python and segment\_anything libraries. Processing logs include image path, index, mask counts, and descriptor outputs (solidity, aspect ratio, complexity) for each connected component per image, allowing any erroneous selections to be flagged for manual inspection.

### Workflow Steps

1.) Image acquisition and pre-processing. A recursive search through the root folder identifies all image files with valid extensions (e.g., .jpg, .jpeg, .png). The pre-processing steps adjust global image properties, including white balance, brightness, contrast, colour saturation and sharpness, and apply mild deblurring and background normalisation.

2.) Mask generation. For each image, SAM generates multiple segmentation masks. We rank these by mask area to prioritise the largest objects, usually bone plus ruler or only bone.

3.) Connected-component extraction. We convert the top mask's segmentation to a binary mask using OpenCV and isolate the N largest connected components (supposedly bones and ruler).

4.) Bone selection heuristic. For each isolated component, we compute three shape descriptors. These descriptors help discriminate between regular, elongated objects (e.g., the ruler) and irregular, concave forms (bone). These descriptors are used to select the bone mask, on the heuristic that measurement rulers and labels tend to be highly solid and regular, whereas bones exhibit variable morphology, concavities and irregular edges:

- solidity = contour area/area of its convex hull;
- aspect ratio = bounding-box width/height;
- complexity (circularity measure) =  $(\text{perimeter}^2) / (4 \pi \times \text{area})$ .

5.) Mask application and export. The selected bone mask is applied to the original RGB image, producing a “bone only” image. The destination path preserves the original folder hierarchy.

6.) Iterative Refinement. The workflow was applied iteratively in three successive passes to maximise segmentation accuracy. The first pass successfully isolated the bone in approximately 90% of images. The remaining mis-segmented cases were automatically reprocessed in a second pass using adjusted parameters (e.g., mask sensitivity and connected-component thresholds). A third pass was then applied to the residual subset of problematic images.

## RESULTS

Preliminary metrics show that the segmentation success rate (bone isolated, ruler/background removed) exceeded 95%. The shape descriptor heuristic correctly identified the bone component in the vast majority of cases, with only sporadic misidentifications in images where the ruler was partially occluded or the bone displayed an extremely regular shape. This integrated dataset, including more than 10000 images, is now ready for the next phases of the AviArch pipeline: (a) augmentation via synthetically generated virtual bones from 3D models to expand training data; (b) training a deep-learning classifier for avian bone taxonomy; (c) integrating classification results into species-community reconstructions and ecological modelling. The processed images are then available for downstream tasks: naming conventions standardised, background cleaned, and folder structure preserving provenance. This enables merging of previously disparate institutional datasets into a common repository.

## DISCUSSION

By situating this workflow within the broader AviArch methodology, several implications emerge. First, the automated segmentation and dataset integration pipeline advances the principle of reproducibility and scalability in zooarchaeological image processing. Where manual segmentation would be

laborious and inconsistent across institutions, our workflow provides a standardised, script-based process suitable for large-scale deployment domestically and internationally.

Second, the cleaned and unified image repository is a prerequisite for AviArch’s future work and aims: deep-learning classification, dataset augmentation, and community-level ecological modelling. Without consistent preprocessing, the AI tools and ecological inferences risk bias (e.g., background artefacts being spuriously learned).

Limitations remain. The heuristic of using solidity for component discrimination may fail in edge cases - e.g., bones with exceptionally regular shapes or rulers partially occluded by labels. Moreover, image quality (lighting, contrast, background clutter) still affects segmentation performance. In future work, we plan to enhance the discrimination step (e.g., via a small supervised classifier on shape descriptors), to run error-flagging loops for mis-segmented images.

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### 337. Generative Modeling for Potteries: A GMM-GAN Based Framework for Completion and Clustering of Pottery Fragments

*Suhui Liu (University of Science and Technology Beijing)*

#### Research Background

The morphology of artifacts carries rich historical and cultural information and is often closely tied to specific temporal and spatial contexts. The outline of an artifact fundamentally determines its morphological characteristics and, therefore, provides critical clues for typological classification and chronological classification. Quantitative methods such as Geometric Morphometrics (GMM), particularly those based on Elliptic Fourier Analysis (EFA), have become widely used in quantitative analysis of pottery outlines. Previous studies have applied GMM to complete potteries or pottery fragments (Ning et al. 2025; Loftus 2022). However, in practical archaeological excavations, artifacts are most often discovered in fragmentary form, and the degree of fragmentation varies significantly. This fragmentation not only complicates morphological reconstruction but also poses major obstacles to typological and historical interpretation.

Generative Artificial Intelligence offers new possibilities for addressing this issue. Generative models, such as Generative Adversarial Networks (GANs), can learn complex image patterns and simulate human cognitive processes to perform image completion tasks (Navarro et al. 2022). In this study, a GMM - GAN based framework is proposed for the completion and classification of pottery fragments. Specifically, this research aims to address how fragmentary pottery can be analyzed and integrated with complete potteries within a unified morphological and classificatory framework in real archaeological contexts. To address this question, the proposed approach first employs a generative network to reconstruct complete vessel outlines from fragmentary inputs, and subsequently evaluates the reconstructed shapes through morphometric analysis and supervised classification to assess their

consistency with established archaeological cultural phases, thereby demonstrating the archaeological meaningfulness of the generated results.

#### Dataset and Method

The dataset used consists of 415 small flat-bottomed jars from the Sanxingdui site, including 400 complete potteries and 15 excavated fragments. Complete vessel outlines were collected from published archaeological excavation reports and standardized into uniform two-dimensional representations. Fragmentary pottery data were acquired through 3D scanning of excavated objects, from which cross-sectional profiles were extracted and converted into outline representations. All outlines were centered and normalized within a  $256 \times 256$  pixel image space, with the vessel silhouette rendered in white against a black background. The complete pottery dataset was split into training, validation, and test sets using a 7:2:1 ratio. To address the limited training sample size, data augmentation was performed in the EFA-derived morphological space. Specifically, Elliptic Fourier descriptors of complete vessel outlines were subjected to controlled perturbations along principal component axes, within  $\pm 2$  standard deviations. These perturbations correspond to plausible morphological variations observed within the assemblage, such as changes in vessel profile curvature and rim expansion, while preserving overall typological structure. For each complete vessel in the training set, eight virtual shapes were generated in its local morphological neighborhood, resulting in an expanded training set of 2,520 outlines. The test set (55 outlines) included complete and fragmentary outlines.

During training, complete vessel outlines were randomly occluded to simulate fragmentary conditions. Polygon-based random masks were applied, covering 30%–60% of the vessel area, in order to expose the network to diverse fragmentation patterns. The generator received the occluded outline as input and was trained to reconstruct the complete vessel using the original outline as ground truth. Network parameters and loss functions were optimized based on pixel-level reconstruction loss between the generated output and the ground truth image. Model performance was first evaluated on the validation set, where controlled occlusion strategies were applied to

diagnostically significant regions, such as the rim and base, to better approximate real archaeological fragments. Reconstruction quality was assessed using Mean Squared Error (MSE), Dice coefficient, and Structural Similarity Index (SSIM), allowing evaluation of both pixel accuracy and structural similarity. These metrics were used to assess whether the generator had successfully learned a completion pattern. Then the trained model was applied to the test set, in which fragmentary inputs were generated by masking either the rim region or the base region to better simulate realistic archaeological fragments. Reconstruction results for test fragments were evaluated using the same quantitative metrics (MSE, SSIM, and Dice coefficient), and the generated complete outlines were saved for further morphometric analysis. On both validation and test sets, the model achieved high scores through metrics, demonstrating robust reconstruction capability and reliability in handling fragmentary potteries.

The reconstructed images were subsequently processed using Geometric Morphometrics (GMM). After Elliptic Fourier Analysis (EFA) and dimensionality reduction via Principal Component Analysis (PCA) on the efourier descriptors, Linear Discriminant Analysis (LDA) was employed as a supervised classification method. The primary objective of LDA is to identify projection directions that maximize the separation between predefined archaeological cultural phases while minimizing variation within each phase. By explicitly incorporating class label information, LDA seeks an optimal projection in which vessels from the same cultural period cluster tightly, whereas vessels from different periods are maximally separated. Through this process, the classifier captures combinations of morphological features that are most diagnostic for cultural periodization. The LDA model was trained using GMM-derived shape features from complete pottery outlines in the training and validation sets, together with their associated cultural phase labels. The trained classifier was then applied to the reconstructed outlines generated by the GAN. Classification results indicate that the predicted cultural phases of reconstructed vessels are consistent with their known archaeological phases, demonstrating that the reconstructed outlines retain typological and

chronological coherence. Overall, the reconstruction process preserves morphologically meaningful features relevant to archaeological classification.

## Conclusion

To conclude, this framework provides a promising approach for applying deep learning to small archaeological datasets. More importantly, the reconstructed shapes are typologically meaningful and consistent with the historical and social meanings revealed by the dataset itself. The framework is inherently extensible and can be adapted in future research by incorporating different artifact types, alternative morphometric descriptors, or modified generative architectures. In this way, it offers a flexible methodological foundation for integrating fragmentary materials into quantitative archaeological analysis.

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## 453. Experimental AI Applications for Rapid Archaeological Legacy Data Distribution

*John Wallrodt (University of Cincinnati)*

Our academic department holds a large collection of physical documentation for various archaeological projects in the Mediterranean. For the past decade, we have been organizing the physical material into new containers and identifying them with the correct hierarchical format. One particular project was excavated in the 1960s in Greece and is still under active research and publication. The publication responsibilities have been passed down to a new generation of scholars who need access to the material that we hold, but they lack the necessary resources to come to our department and view the tens of thousands of documents, notebooks, photographs, field plans, and drawings that this project created. We have started a new program of digitizing the materials associated with this project, focusing on well-considered processes, database automation, and the use of AI for data extraction of these materials.

This paper describes our overall approach to this collection and how we have used the resources of a single academic department to digitize the material, and highlights some of our experimentation with parallel data extraction methods (for both archival and archaeological purposes).

This paper will specifically describe the methodology for indexing almost 5,000 typed index cards (for pottery) from the project with the aim towards ingesting the results into the archival database but also break down the data into various fields (object number, object type, notebook pages, photographs, description, etc.) to form the genesis of an archaeological database. We are looking at the cost (mostly in terms of people hours) to run both analyses simultaneously. The techniques include textual grep patterns via python, untrained AI using AI generated OCR with coordinate data, and trained Document AI from Google. The results of these methods are compared to a subset of items that have been hand-entered.

## S30: Unstoppable Vision, Immovable Practice: An Adversarial Debate on Linked Open Dreams and the Reality of Archaeological Data Collection

*Fabian Riebschläger, German Archaeological Institute*

*Helmut Schwaiger, Austrian Archaeological Institute*

*Lisa Steinmann, German Archaeological Institute*

*Brigitte Danthine, Austrian Archaeological Institute*

**Location:** Hörsaal 02

**Session Format:** Other

*We wish to include lectures and debate: Our vision would be two have two “adversarial lectures” based on actual project experience followed by a debate slot of ca. 10-15 minutes. This way we can discuss the pros and cons as evident from the experience of researchers at all career stages and from varied institutional and geographical backgrounds and from project results as well as everyday archaeological practice. It is important for the concept of this session to be able to integrate contrary perspectives and thus identify common ground or irreconcilable differences via these debate slots.*

*‘Adversity is the first path to truth.’ (Lord Byron)*

This year marks a quarter century since the publication of Tim Berners-Lee’s influential vision of “The Semantic Web”<sup>1</sup>. Humanity’s relationship to the internet has changed drastically since 2001, but especially in data-based research, few visions have remained as mesmerising and as promising as that of the Semantic Web. The paradigm of semantic data, together with related concepts such as knowledge graphs, Linked Open Data (LOD), ontologies and

authority files / controlled vocabularies has produced a wealth of research and implementation work over more than two decades.

This vision of the Semantic Web has also swept across archaeology, a discipline which has a keen interest in making sense of complex, often incomplete or even subjective data that is, sometimes obviously sometimes subtly, linked conceptually and contextually, yet produced under highly varied research designs and data-collection practices.

However, the perceivable impact of all these semantic investments remains surprisingly small in everyday archaeological practice, which continues to be dominated by simple tabular and other conventional data structures. Moreover, recent advances in AI have suggested that general-purpose, data-driven methods often outperform carefully engineered knowledge systems—a ‘bitter lesson’ articulated by Richard Sutton (2019)<sup>2</sup>.

This session attempts a critical reappraisal of the ‘semantic vision’ in archaeology, its current state and potential future. For this purpose, we invite contributions from two ‘opposing camps’: those who showcase why semantic approaches should shape the future practice and those who argue why traditional data structures continue (and perhaps should continue) to dominate data production and analysis. Contributions may focus on theoretical or practical aspects, on merits or shortcomings of both ‘camps’, or any mixture thereof.

In this way, the session will address a number of key questions and issues, including:

- Why are the promises of semantic data so important to archaeologists, and which of them, have been fulfilled so far?
- How accessible and maintainable are semantic approaches in practice?
- When is the cost of semantic data modelling justified by demonstrable gains?
- How does everyday field work and data collection (capture?) need to change to accommodate, incorporate, or be driven by semantic approaches?

- Is the semantic paradigm outdated in the age of AI? Do we need a specific machine-language, if the machines now understand our language?
- What are the reasons for the success and longevity of non-semantic approaches?
- What are the reasons for the success and lasting popularity of semantic approaches?
- What core strengths of non-semantic data might be threatened if semantic approaches become prevalent?
- Are there visions for complementary roles or hybrid workflows between statistical/ML methods and explicit knowledge representation: Do efficient ways exist to reconcile semantic approaches with conventional data structures without adding redundant workload?

As the title suggests, the session has been designed to be adversarial in nature, based on the assumption that ‘you cannot have your cake and eat it, too’: given the high investment in different skills and infrastructures necessary to make use of both approaches and their radically different nature, a parallel approach with redundant data collecting and provisioning practices in both semantic and traditional data models seems not feasible. Or could we envision a way to reconcile the differences without creating inefficient redundancies and thus, have our cake and eat it, after all?

With this in mind, the session is intended to provide a forum for robust yet fair arguments and a lively debate, grounded in the realities of limited funding, (un)realistic demands made of archaeologists’ skill sets, and the need for clear and practical research directives in the (next) coming age of austerity in academia. To ensure a rich and representative debate, we explicitly encourage contributions from early-career scholars, colleagues from geographically and institutionally under-represented regions, and researchers working outside of traditional academic networks. Our goal is to provide the space for constructive discussions among a diverse group of people and perspectives, reflecting the wide spectrum of archaeological research and researchers.

## References:

- 1 Berners-Lee, T., Hendler, J. and Lassila, O. (2001) 'The Semantic Web', Scientific American, May, pp. 29–37.
- 2 Sutton, R.S. (2019) The Bitter Lesson. Available at: <http://www.incompleteideas.net/InIdeas/BitterLesson.html> (Accessed: 28 August 2025).

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| <b>13:30 –<br/>13:50</b> | 86. Iconographic Metadata: From 'Traditional' Databases to Semantic Data<br><i>Melissa Bergoffen (BSA Library); Maria Papadopoulou (TALOS); Artemis Karnava (University of Crete); Christophe Roche (TALOS)</i> |
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| <b>13:50 –<br/>14:10</b> | 426. Between Promise and Practicality – Lessons from the NFDI4Objects<br><i>Fabian Fricke (German Archaeological Institute); Mattis thor Straten (CAU Kiel)</i> |
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| <b>14:10 –<br/>14:30</b> | 434. Table2RDF: From Everyday Spreadsheets to Reusable RDF. A Generic, Understandable Workflow for Archaeology<br><i>Brigit Danthine (Austrian Archaeological Institute); Gerald Hiebel (University of Innsbruck)</i> |
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| <b>14:30 –<br/>14:50</b> | 437. Between semantic vision and excavation practice: Linked Open Data at an archaeological research institute - an honest situation report<br><i>Helmut Schwaiger*, Brigit Danthine*; Karl Burkhart*; Micheline Welte*</i> |
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*\* Austrian Archaeological Institute*

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| <b>14:50 –<br/>15:00</b> | Discussion |
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## 86. Iconographic Metadata: From 'Traditional' Databases to Semantic Data

*Melissa Bergoffen (BSA Library)*

*Maria Papadopoulou (TALOS)*

*Artemis Karnava (University of Crete)*

*Christophe Roche (TALOS)*

Within a world that is becoming increasingly more digital, cultural heritage institutions like museums are bringing their collections online for remote access by the public. And the public doesn't have to search far; renowned institutions like The Metropolitan Museum of Art, The British Museum, and the Bibliothèque nationale de France all have searchable collections of the archaeological artifacts and other art pieces they safeguard physically. There are even projects specifically for more heterogeneous collections, like Europeana and SearchCulture. While having the ability to view these objects virtually from anywhere in the world is an astounding advancement in access to knowledge and culture, is the data retained and presented by these museums within their catalogs useful for any audience, whether that be the general public or trained specialists? This is particularly an issue when it comes to the presentation of iconographic material (both archaeological and modern) and their metadata, as other, more 'objective' information such as dates, provenance, and publications have already been easily and consistently recorded. The four members of TALOS' Research Topic 2 on Classifying and Naming Objects will explore how iconography is currently being handled, how that addresses the needs of its audience, and various methods and technologies that can be used to make improvements.

Currently, due to restrictions based on time, funding, digital storage space and more, museums may not strictly adhere to standards for documenting cultural metadata put forth in Baca's guide (Cataloging Cultural Objects: A Guide to Describing Cultural Works and their Images), or those of VRA Core 4.0 (a data schema for visual objects), or even ICONCLASS. Instead, they record the minimum amount of information that is useful to researchers, which often means that metadata such as object type, identification number, provenance and creation are deemed more important than that of iconography.

This is a major pitfall because researchers of iconography, a subfield of archaeology and art history that has existed since the 18th century, require access to this kind of information, but are unfortunately unable to access it currently at a level of depth that would be useful. For example, an expert researcher might be interested in the depiction of a specific type of clothing, and would want to perform searches for that piece of clothing through online catalogs containing iconographic artifacts, but that search would result in nothing useful if the iconography has not been accurately and completely cataloged. This lack of consistent and complete iconographic metadata does not only affect experts, though, but also the general public, who most likely care about the images themselves rather than provenance and other prioritized metadata. Instead, they tend to search for the subjects of what is being depicted, and again, if the iconographic data is not complete or consistent, problems may arise for those conducting searches.

In order to meet the iconographic needs of both the general public and more specialized scholars, it is important to create a consistent methodology of approach, since currently one does not exist. TALOS' PhD Candidate has been working on an iconographic methodology that combines the approaches set forth in Sourvinou-Inwood's 'Reading' Greek Culture: Texts and Images, Rituals and Myths and Stansbury-O'Donnell's Pictorial Narrative in Ancient Greek Art. Essentially, every detail of a depiction must be described in exhaustive detail, near to the point of excess, in order to prevent bias in what iconographical elements are given priority. This means that everything from the figures, their dress and gestures, the objects they interact with, the actions they perform, the scenes they are set in, and the themes they are used

to convey must be included in any iconographic description. This could get complicated and messy pretty quick, especially if the practice of entering metadata for each individual object continues to be followed, and if each institution uses their own preferred vocabulary.

A better way to approach iconographic metadata, then, can be through the implementation of Semantic Data, the paradigm of which could represent a decisive shift in the way iconographical information can be modelled, integrated, and interpreted. Through ontologies, knowledge graphs, and Linked Open Data (LOD), archaeology and other related fields gain a framework for representing the conceptual and contextual relationships that underlie heterogeneous data sources: artifacts, their iconography, or any publications about them. Ontologies such as CIDOC CRM enable archaeologists to formalise the semantics of data in RDF/OWL, allowing machines to reason about implicit connections and scholars to query distributed datasets through SPARQL, the language for querying RDF Knowledge Graph. These semantic technologies transform archaeological data from isolated repositories into an interconnected web of cultural knowledge. In contrast to traditional relational databases, which privilege local consistency and rigid schemas, semantic graphs enable interoperability across institutions and the ability to perform cross-disciplinary reasoning on temporal, spatial, and conceptual dimensions of heritage. They encourage a new epistemology, one that views archaeological interpretation as a network of hypotheses that can be explicitly modelled, linked, and discussed.

Semantic Data, therefore, would be able to adequately accommodate the large amount of iconographic metadata that visual artifacts possess. This has been tested through the creation of an ontological framework for female representations on artifacts from the Bronze Age Aegean. This framework defines concepts concerning the aforementioned iconographic elements, providing relationships between them, and also links to other important information (i.e. geographic location, scholarship, provenance). The efficacy of the resulting knowledge graph can then be queried via SPARQL expressions, illustrating how the relations of the concepts can be used to perform more detailed iconographic searches.



To summarize, it is our aim to analyze current practices concerning iconographic metadata, and demonstrate how they can be improved through the use of Semantic Data as evidenced via a case study on competency questions applied to an iconographic ontology concerning female representations within Bronze Age Aegean wall paintings.

Bikakis, Antonis, Robert Ferrario, Stephane Jean, Beatrice Markoff, Alessandro Mosca, and Marianna Nicolosi Asmundo, eds. 2024. *Semantic Web and Ontology Design for Cultural Heritage 2024*. Proceedings of the fourth edition of the International Workshop on Semantic Web and Ontology Design for Cultural Heritage. Tours, France, October 30-31, 2024. France. <https://ceur-ws.org/Vol-3809/>

Baca, Murtha, Patricia Harpring, Elisa Lanzi, Linda McRae, and Ann Whiteside. 2006. *Cataloging Cultural Objects: A Guide to Describing Cultural Works and Their Images*. American Library Association.

Sourvinou-Inwood, C. 1991. *‘Reading’ Greek Culture: Texts and Images, Rituals and Myths*. Oxford University Press.

## 426. Between Promise and Practicality – Lessons from the NFDI4Objects

*Fabian Fricke (German Archaeological Institute)*

*Mattis thor Straten (CAU Kiel)*

Running a productive Knowledge Graph in archaeology is far more complex than it may appear. Within NFDI4Objects, the VZG-GBV operates the RDF-based Knowledge Graph ([graph.nfdi4objects.net](http://graph.nfdi4objects.net)), integrating heterogeneous data from various sources. While the semantic approach offers clear advantages—interoperability, flexible querying, and long-term data publication—it also reveals technical and conceptual limitations. Performance issues of triple stores compared to relational databases remain a major

challenge, particularly when scalability and stability are required for everyday use.

Arbodat+ and Poseidon, two services out of the NFDIObjects portfolio, continue to rely on relational backends. To bridge this gap we are developing within NFDI4Objects workflows to represent the data of these services in the KG. This contribution discusses the practical experience of bridging these paradigms, outlining lessons learned about when semantics genuinely add value—and when the conventional, relational model still proves the more robust choice for sustainable archaeological data management.

## 434. Table2RDF: From Everyday Spreadsheets to Reusable RDF. A Generic, Understandable Workflow for Archaeology

*Brigit Danthine (Austrian Archaeological Institute)*

*Gerald Hiebel (University of Innsbruck)*

### Introduction

Amid the debate between ambitious semantic visions and everyday archaeological practice, Table2RDF is introduced as a lightweight Python GUI and workflow that provides a simple path to RDF generation from ordinary spreadsheets. The workflow is designed to be as generic as possible yet as understandable as possible, lowering the barrier so that RDF production becomes easier and more broadly applicable in routine settings.

Producing FAIR RDF from everyday research remains challenging and cumbersome. To address this, Gerald Hiebel developed the “generic CRM excav modelling”-Pipeline (based on the “Spreadsheet to RDF”-pipeline, Hiebel 2022 [1]). To get around the fact that different steps with different scripts have to be carried out in several different programmes, Table2RDF [2] was developed. Table2RDF is a lightweight Python GUI that operationalizes this five-step, generic pipeline for semantic publishing aligned with CIDOC CRM (ISO 21127:2023 [3]) and extensions. CIDOC CRM is a widely used, event-

based concept reference model for cultural heritage, along with its extensions.

The pipeline (1) ingests an Excel workbook and selects sheets for export; (2) exports and validates namespace prefixes to ensure consistent URIs; (3) derives deterministic identifiers from tabular data via a local PostgreSQL installation – without user-written SQL; (4) applies ontology mappings in Ontotext Refine against CIDOC CRM and domain extensions; and (5) loads machine-actionable RDF into GraphDB, either into an existing repository or a newly created one, with optional cleanup.

#### Methods and materials

In the excel-sheet each line contains one information in the following form:

- ID of domain – unique identifier of the subject.
- Domain label – human-readable label (specify once per ID).
- Class of domain – ontology class of the subject (specify whenever used).
- P3\_has\_note – optional note on the domain.
- Property – relation between domain and range.
- ID of the range / Range label / Class of the range – identifier, label (once), and class (whenever used) of object.
- Dot one – property of the dot one for this specific triple
- Dot one target - the Dot one target name
- Proposition set – named graph.

To support rapid onboarding, a fictive, ready-to-adapt example is provided in the project's GitHub repository. It consists of: Three namespaces (S20, A8, E19), one place with one excavation including start and enddates as literals, one sondage with two stratigraphical units with two findings each. The findings have material and type as well as their finding coordinates attached. The presentation also highlights real-world applications across heterogeneous projects.

A provided minimal, domain-agnostic example captures identifiers, labels, classes, relations, and optional notes as well as dot one properties and can serve as template or guiding principle to model the own data. Exports with

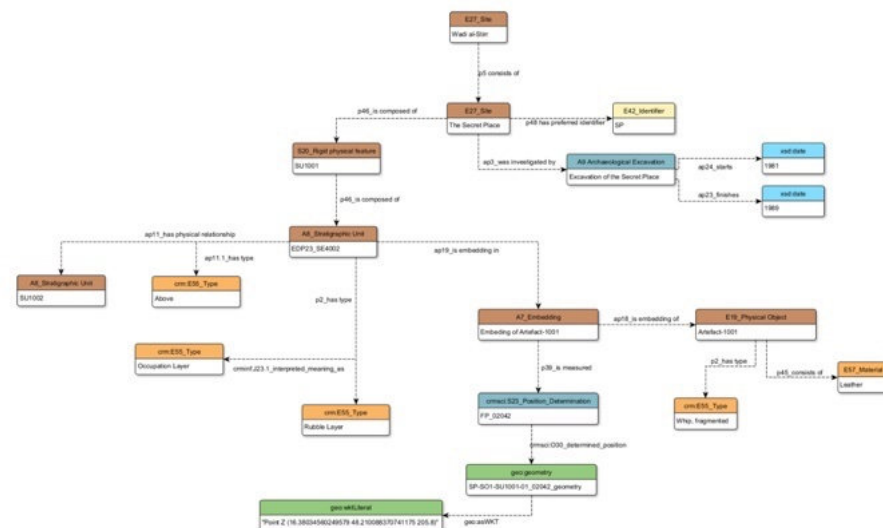
and without literals are separated to keep identity management and data enrichment auditable.

With this its intended to demonstrate how a single, generic table structure plus reproducible mappings enables heterogeneous projects to publish interoperable graphs with low onboarding effort.

#### Results and Discussion

Table2RDF tries to make the RDF-creation-pipeline easy usable for everybody, whereby the generic RDF-creation-pipeline makes it possible to generate RDF data easily in the first place. Beyond convenience, the wider implication is scalable interoperability: a single, generic table structure plus reproducible mappings lets diverse projects publish compatible graphs without re-engineering their pipelines. This lowers onboarding costs, improves data quality and documentation, and accelerates integration with existing LOD ecosystems and analytical platforms. Future work will also dot-two-properties and additional mapping to the implementation generic one specified for excavations.

The approach acknowledges that ontologies as shared “thinking models” are now widespread in digital archaeology – e.g., in initiatives such as ECCCH and ARIADNE – yet often encounter skepticism due to perceived complexity and limited usability. By embracing familiar spreadsheet practices and adding only the semantic structure required for interoperability, the workflow seeks a pragmatic middle ground. In the spirit of Session S30's adversarial format, the talk will indicate where this path succeeds, where it falls short, and how it may help reconcile semantic aspirations with day-to-day data collection.

[illegible]

The lecture presents an unembellished insight into the situation at an archaeological research institute. It is based on an internal survey of scientific and technical staff that reveals attitudes, expectations, competences, practical hurdles and everyday compromises in dealing with structured data and semantic concepts. As a concrete framework, we draw on the institute's existing modular infrastructure, which is intended to be expanded further: an online database for archaeometric data, a management system for digital assets (e.g. images, 3D models, RTI, research data), a certified repository for long-term preservation, an online application for numismatic data, and a SKOS-based vocabulary hub. The database for archaeometric data is being developed as a multi-proxy platform covering a wide spectrum of inorganic

materials and artefacts (ceramics, lithics, pigments, mortars, glass, metals, and corresponding raw materials), harmonizing results from petrographic, mineralogical, geochemical, isotopic, (bio)molecular and microstructural analyses (1). The application for recording coins found in excavation provides a structured environment for the documentation, analysis, and dissemination of coin data using controlled vocabularies and the NUDS schema, and is designed for integration with Nomisma (2). The digital asset management system functions as the central platform for images, videos and other digital assets. It supports a wide range of 2D and 3D formats, offers controlled vocabularies and authority links, and currently manages several hundred thousand records with a growing Open Access component. The thesauri, published via Vocabs, aggregate controlled vocabularies derived from institute-wide data structures to improve indexing, multilingual access and interoperability. Within this landscape, the survey investigates where ontologies and LOD approaches align with or conflict with project realities: Where do they fail due to existing workflows, terms, tools, and expectations? Which requirements are perceived as realistic or excessive? How do these infrastructures support – or fail to support – the everyday work of researchers?

## Results

Previous experience at the institute shows a heterogeneous picture, which is to be systematically collected and substantiated by the survey. There are colleagues who are in fact not available for requirements such as LOD, controlled vocabularies and ontologies - whether due to overload, scepticism or a lack of perception of relevance. There is also a group that open to practical arguments, as well as those who are generally open to semantic approaches, as long as the concrete added value for their own research is clearly recognisable. At the same time, a central structural hurdle becomes clear: The implementation of LOD standards requires resources, project durations, and targeted funding. This requires the willingness to raise funds for data and methodological work - often in competition with classically understood 'specialised research'. In addition, there is a widely reported tension between research and method development: semantic modelling is often not

recognised as an independent scientific achievement but is perceived as an additional effort. Our impression of this area of tension forms the starting point; the survey is intended to empirically support and differentiate these observations and thus create a reliable basis for further discussions on realistic strategies, priorities and support formats (3).

## Discussion

Instead of demonising LOD and ontologies or glossing over their implementation, we advocate a sober stocktaking as a prerequisite for viable strategies. Based on the survey results, we discuss possible future perspectives: low-threshold forms of communication, responsible minimum standards, targeted support services and scenarios in which semantic approaches and established working methods can be productively combined. The article is intended as an invitation to an open discussion on how 'semantic dreams' can be made compatible with the actual conditions of archaeological research practice.

## References

- (1) Micheline Welte, Karl Burkhart, Helmut Schwaiger, Vasiliki Anevlavi, Emmanouil Anevlavis, Pamela Fragnoli, Walter Prochaska, Innovative archiving of raw materials: Advancing archaeometric databases at the Austrian Archaeological Institute/Austrian Academy of Sciences, *Journal of Archaeological Science: Reports*, Volume 67, 2025, 105354, ISSN 2352-409X, <https://doi.org/10.1016/j.jasrep.2025.105354>.
- (2) <https://github.com/ewg118/NUDS>
- (3) M.D. Wilkinson, et al. The FAIR Guiding Principles for scientific data management and stewardship *Sci. Data*, 3 (2016), Article 160018, 10.1038/sdata.2016.18

## S31: Computational Archaeology Revisited: Building Bridges with Mathematics and Computer Science

*Eythan Levy, University of Zurich*

*Martin Hinz, Kiel University*

**Location:** Hörsaal 01

**Session Format:** Other

The official [mission statement](#) of CAA states:

“Computer Applications and Quantitative Methods in Archaeology (CAA) is an international organization bringing together archaeologists, mathematicians, and computer scientists. Its mission is to encourage and facilitate dialogue between these disciplines, to provide an overview of the present state of the discipline, and to stimulate discussion to progress the field.” (emphasis ours)

Yet, in practice, mathematicians and computer scientists are still under-represented, and most contributions come from archaeologists as end-users rather than as co-developers of new methods. In the early days of computational archaeology, cross-disciplinary collaboration was more common. Especially in the seventies, the pioneering work of the 1970 Anglo-Romanian Conference on Mathematics in the Archaeological and Historical Sciences conference (Hodson, Kendall and Tautu 1971) brought together a whole array of mathematicians proposing concrete mathematical and computational solutions to archaeological problems. This period also saw the publication of the seminal work of Doran and Hodson on Mathematics and Computers in Archaeology (1975), which embodied the state-of-the art of computational/quantitative archaeology of the time — producing techniques such as seriation algorithms that remain influential today.

Since then, there have been notable breakthroughs, such as Bayesian approaches to radiocarbon dating (Buck et al. 1991; Bronk Ramsey 2009), the application of spatial point process models to settlement patterns, and the adaptation of phylogenetic and network-theoretical methods to study cultural transmission. Yet overall, the field has leaned more towards ready-made tools (GIS, network analysis, semantic modelling, AI applications) than to the joint development of novel mathematical or algorithmic frameworks.

This session aims to reinvigorate that dialogue. Our vision is a CAA that not only showcases applications but also nurtures collaborations where new mathematical models and computational techniques are developed for and with archaeology.

The intended round table would feature the following parts:

- General introduction and problem statement (Levy and Hinz).
- Short interventions by mathematicians, computer scientists, and archaeologists. Mathematicians and computer scientists would present techniques of their choice, which they feel might be of use for archaeology. The intention is, for the archaeological community, to discover techniques they might not be aware of, and which might have significant impact on future quantitative archaeological research. Archaeologists are also invited to present open problem statements: concrete case studies for which they failed to find practical quantitative or algorithmic solutions among the standard toolkits. Each intervention would consist of a short presentation, followed by a longer discussion with the audience.
- Brainstorming part. General discussion, hoping to find convergences between the exposed archaeological needs and available computational techniques presented.

We invite colleagues from all three disciplines to participate actively, especially in presenting open problems or potential solutions. Colleagues wishing

to present either a mathematical/computational technique of their choice, or an open problem, are invited to submit an abstract to the session via the conference’s standard abstract submission system.

References:

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1): 337–360.

Buck C.E., Kenworthy J.B., Litton C.D., Smith A.F.M. 1991. Combining archaeological and radiocarbon information: a Bayesian approach to calibration. *Antiquity* 65(249):808–21.

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Hodson, F.R., Kendall, D. G., Tautu, P. (eds). 1971. *Mathematics in the Archaeological and Historical Sciences*. Proceedings of the Anglo-Romanian Conference, Mamaia, 1970. Aldine-Atherton, Inc., Chicago.

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| 10:30 – 12:30 | <ul style="list-style-type: none"><li>• Introduction<br/><i>Eythan Levy, Martin Hinz</i></li><li>• 125. Herculaneum Scrolls Ink Detection Using Textural Features<br/><i>Oleksandr Korotetskyi (Czech Technical University); Michal Haindl (Institute of Information Theory and Automation, Czech Academy of Sciences)</i></li><li>• 127. Probabilistic Geometric Joining for Fragmented Paper: An Algorithmic Pipeline with Markov Assembly under Minimal Supervision<br/><i>Terrindeep Sandhu (University of California, Los Angeles); Deborah LaCamera (Studio TKM Associates); Heini Korhonen (Studio TKM Associates); Kay Horak (Studio TKM Associates); Lorraine Bigrigg (Studio TKM Associates); Marie Lassaigne (University of Southern California, Los Angeles)</i></li></ul> |
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| 12:30 – 13:30 | Lunch break             |
| 13:30 – 14:30 | Discussion, Round Table |

125. Herculaneum Scrolls Ink Detection Using Textural Features

*Oleksandr Korotetskyi (Czech Technical University)*  
*Michal Haindl (Institute of Information Theory and Automation, Czech Academy of Sciences)*



This paper addresses pixel-level ink detection in unwrapped Herculaneum scroll imagery (the Vesuvius Challenge) using non-neural pattern-recognition and machine-learning methods combined with carefully selected textural features. Recovering ink from these volumetric X-ray/phase-contrast image stacks is crucial for making lost texts accessible to scholars—particularly in cases where neural methods may be impractical due to limited training data, interpretability requirements, or other constraints. Although deep-learning approaches currently dominate many recognition tasks, there is still large room for alternative strategies. This study explores whether a transparent, data-efficient, non-neural pipeline can still achieve meaningful ink-background separation and serve as a reproducible baseline for future comparisons. The data used in this study were obtained from the EduceLab-Scrolls dataset.

In the present work, we explore how several classical methods can be combined to detect ink patterns effectively in already segmented scrolls. We apply multiple texture descriptors and Markov Random Fields (MRFs), together with unsupervised segmentation using K-means clustering, to create homogeneous image regions. To improve class separability and stabilize covariance estimates, we use Principal Component Analysis (PCA) for dimensionality reduction. The resulting lower-dimensional features are primarily classified using a pooled-covariance Bayesian classifier, with Linear Discriminant Analysis (LDA) included for comparison. When appropriate, simple spatial regularization is applied to smooth results and reduce speckle noise. Each method was chosen not only for its effectiveness but also for its ability to shed light on how individual features contribute to the overall classification.

Evaluation was performed on a custom benchmark based on segmented images of the EduceLab-Scrolls dataset, using pixel-wise comparisons between our binary predictions and the provided ones, treated as reference ground-truth masks for the primary performance metric. Although our results currently fall below reported neural-network baselines, the experiments demonstrate that non-neural methods can still be useful in ink recovery tasks

with limited training data, while also revealing specific failure modes inherent to such approaches. These findings suggest that thoughtful integration of the discussed methods could potentially enhance existing ink-detection models, and several promising directions for further refinement are outlined, including adoption of more suitable textural features and the use of more sophisticated classification methods.

## 127. Probabilistic Geometric Joining for Fragmented Paper: An Algorithmic Pipeline with Markov Assembly under Minimal Supervision

*Terrindeep Sandhu (University of California, Los Angeles)*

*Deborah LaCamera (Studio TKM Associates)*

*Heini Korhonen (Studio TKM Associates)*

*Kay Horak (Studio TKM Associates)*

*Lorraine Bigrigg (Studio TKM Associates)*

*Marie Lassaigue (University of Southern California, Los Angeles)*

### Introduction

Reassembling torn or fragmentary paper (letters, ledgers, maps) is slow, expert-intensive work, and results can be hard to reproduce. We present an algorithmic pipeline—geared to collections work rather than a tool demo—that treats joining as a probabilistic and topologically constrained matching problem, then assembles pages by selecting the most likely joins step-by-step with a simple Markov process. This approach seeks to reduce manual labeling, keep decisions auditable, and scale to full pages. We situate our work alongside early outline-based joining in archaeology and computer vision (da Gama Leitão and Stolfi 1998), recent community efforts to benchmark realistic reassembly problems (Tsesmelis et al. 2024), and manuscript-oriented segmentation studies such as those on the Dead Sea Scrolls (Brown-

deVost, Kurar-Barakat, and Dershowitz 2024). Test images are high-resolution photographs of fragmented sheets (Image credit: New Bedford Free Public Library, New Bedford, MA, USA).

## Methods and Materials

Data preparation focuses on producing consistent photographs and separating paper from background with a simple color/brightness model that is robust to common biases (e.g., slightly beige paper on a whiter backdrop). Resulting fragment silhouettes are converted to clean contours that capture overall shape and local tear features without overfitting noise.

For any two fragment edges, we compute an intuitive compatibility score that rewards close, smooth fits and discourages gaps or overlaps; we also consider subtle color continuity across a proposed seam. These scores are converted into probabilities so that different candidates can be compared on the same scale.

The assembly step treats fragments and candidate joins as a graph. A lightweight Markov assembly then grows the page by repeatedly accepting the next most probable, feasible join. Feasibility is defined by basic topology: fragments must embed in the plane without crossing or self-intersection, inside/outside orientations must remain consistent, and simple page-level checks (e.g., avoiding impossible holes) keep the reconstruction sensible. Because the probabilities carry most of the weight, only minimal supervision is needed: a small number of confirmed or rejected seams can train a simple ensemble re-ranker to nudge choices, but the pipeline remains useful even with zero labels (cf. the spirit of geometry-first approaches in early work and the push for standardized evaluations in recent datasets: da Gama Leitão and Stolfi 1998; Tsesmelis et al. 2024). The segmentation stage and imaging considerations parallel lessons from manuscript conservation, including DSS fragment imaging (Brown-deVost, Kurar-Barakat, and Dershowitz 2024).

## Results

We will report (i) segmentation reliability across typical lighting/backgrounds; (ii) suggested-join quality (how often a correct mate appears among

the top few proposals); (iii) page completeness and seam quality for final reconstructions; and (iv) label efficiency, showing that a small number of labeled examples provides a modest improvement over the unlabeled baseline. Brief ablations will illustrate the practical value of contour simplification and explicit topological checks.

## Discussion

For practitioners, the value is twofold. First, the method is explainable: every proposed join comes with a probability and a clear reason it was accepted or rejected. Second, it is practical: the topological rules mirror curatorial common sense (no overlaps, coherent page shape), while the probabilistic scoring turns “eyeballing” a fit into a reproducible decision. By keeping supervision light, the pipeline supports quick triage and iterative refinement on real collections. Although we focus on flat paper, the same ideas transfer to other planar heritage materials (papyri, posters, prints) and can inform 3D scenarios. More broadly, the work aligns with the field’s move from ad-hoc puzzle solving toward shared, testable procedures and comparable benchmarks (da Gama Leitão and Stolfi 1998; Tsesmelis et al. 2024; Brown-deVost, Kurar-Barakat, and Dershowitz 2024).

## Keywords

Computational archaeology; probabilistic geometry; topology; planar embedding; fragment reassembly; Markov assembly; documentary heritage.

## References

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- [2] Tsesmelis, Theodore; Luca Palmieri; Marina Khoroshiltseva; Adeela Islam; Gur Elkin; Ofir Itzhak Shahar; Gianluca Scarpellini; Stefano Fiorini; Yaniv Ohayon; Nadav Alali; Sinem Aslan; Pietro Morerio; Sebastiano Vascon; Elena Gravina; Maria Cristina Napolitano; Giuseppe Scarpati; Gabriel Zuchtriegel; Alexandra Spühler; Michel E. Fuchs; Stuart James; Ohad Ben-Shahar; Marcello Pelillo; and Alessio Del Bue. 2024. “Re-assembling the

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## 265. Multiple testing of local maxima for detection of post holes

*Valentina Cammarota (Sapienza University of Rome)*

We present a topological multiple testing scheme for detecting peaks (signal) under isotropic Gaussian noise, tests are performed at local maxima of the observed field.

The proposed statistical methodology is designed to analyse post hole data produced in preventive archaeology.

Preventive archaeology enables the rapid surveying of large-scale areas, generating extensive datasets such as detailed site maps that often reveal thousands of closely spaced post holes distributed across several hectares. The aim of the proposed topological multiple testing scheme is to minimise false detections of post holes.

Motivated by this application, our setting is different from the standard large domain asymptotic framework, and it is highly relevant to realistic experimental circumstances.

In particular, we focus on a high-frequency asymptotic regime in which a single realisation of a smooth isotropic Gaussian field (representing background noise) is observed, and a number of well-localised signals (corresponding to post hole locations) are superimposed on this background.

## 383. What Can Ecological Statistical Methods Bring to Archaeological Research?

*Fabrice Rossi (Université Paris Dauphine)*

As highlighted in E. R. Crema's recent survey, statistical modelling remains underdeveloped in archaeology, particularly when compared to adjacent disciplines such as ecology. In this presentation, I will argue that, beyond merely mimicking the use of standard statistical techniques like multilevel modelling from ecology, archaeologists can benefit from applying techniques specifically designed for ecological research.

An example of this benefit can be seen in Feugnet et al. (2017), where the authors utilise a null model from ecology to assess the significance of the co-presence of Mediterranean imports in Celtic settlements. The connection to ecology is made by equating artifacts to species and settlements to environments. This approach allows the use of methods designed specifically to study species abundance, particularly null model approaches. These involve designing plausible models of abundance with minimal structural hypotheses and testing whether the data can be used to reject them, thereby suggesting an existing structure. In the case of artifact co-presence, the idea is to assume that artifacts are distributed randomly within the settlements, maintaining both the overall number of objects of each type and the total number of objects in each settlement constant. The paper demonstrates that this ecological approach yields quite different results from a naive counting approach.

More generally, I will argue that numerous methods designed to study species abundance, such as those described in Chao et al. (2020), could be incorporated into archaeological analyses, albeit with some caveats. This is certainly a promising research project that would require collaborative efforts from statisticians familiar with the ecological literature and

archaeologists who can assess the adequacy of the hypotheses used in null models and, more broadly, in ecological models.

Crema, Enrico R. 2025. 'Statistical Modelling in Archaeology: Some Recent Trends and Future Perspectives'. *Journal of Archaeological Science* 180 (August): 106295. <https://doi.org/10.1016/j.jas.2025.106295>.

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## 410. Evolutionary Algorithms: An untapped resource for archaeologists?

*Mathys du Plessis (Nelson Mandela University)*

Mathematical optimisation refers to the process of iteratively refining the proposed solution to a problem until a satisfactory result is reached. Classical optimization approaches achieve this goal by formulating the problem as a mathematical function and then use derivative information to refine the parameters of the function to obtain a solution to the problem. In contrast, Evolutionary Algorithms (EAs) are optimization algorithms that are inspired by biological evolution. Potential solutions to the problem are viewed as individuals in a population. Initially, individuals are randomly created (i.e. simply random guesses at a solution). The population of solutions are then

evolved through an iterative process which involves selection, crossover, mutation and fitness evaluation. A fitness function measures how well each of the individuals solve the problem relative to the other individuals in the population. The better, more fit, individuals are then probabilistically selected as parents to produce an offspring population. Offspring individuals are created by combining the solutions represented by parent individuals through genetic crossover. Small random variations called mutations are introduced into offspring individuals. The offspring population replaces the original population and the entire process is repeated until an adequate solution is found.

A significant advantage of EAs over classical optimization algorithms is the at fitness function does not have to be differentiable or continuous and does not have to give an absolute measure of the quality of a potential solution, merely a relative measure with respect to other individuals. Consequently, EA provides much more flexibility to the researcher to specify arbitrary desirable characteristics of the problem solution.

A simple example of how an EA can be used in archaeological research is as a technique to solve the seriation problem faced by Sir Flinders Petrie when he had to determine the chronological order of a series of tombs based on the artifacts discovered. Petrie manually ordered the tombs in such a way that tombs that contained similar artifacts were placed closely chronologically. An EA could represent the ordering of the tombs in an individual by associating each tomb with an ordering number. An ordering of the tombs can be found by sorting the tombs based on their ordering numbers. The initial random population can be made by creating a population of individuals where each individual has a random ordering number associated with each tomb. The fitness function can be a count of the number of artifacts that are shared between successive tombs in each ordering represented by each of the individuals. A high count would thus represent a highly fit individual which should thus be given a high chance of producing offspring. Crossovers between parent individuals would involve randomly selecting either of the parent's ordering number for each tomb to create an offspring individual. Small random numbers can be added to the offspring's ordering

numbers as mutations. Repeating this process should yield a realistic chronological ordering of the tombs.

EAs could potentially be applied to many currently challenging problems in archaeological research if awareness can be raised, and may produce many opportunities for collaboration between computer scientists and archaeologists.

## S36: Composed for Success: Making the Most of Chemical Data in Archaeometry

*Michaela Schauer, Vienna Institute for Archaeological Science (VIAS) of the University of Vienna & Natural History Museum Vienna (NHMV)*

*Michelle Richards, School of Geography, Earth and Atmospheric Sciences, University of Melbourne*

*Brandon L. Drake, Department of Anthropology, University of New Mexico*

**Location:** Hörsaal 01

**Session Format:** Standard

Archaeological data from XRF, LIBS, ICP-MS, FTIR, and Raman spectroscopy is rapidly increasing as these techniques become more accessible, affordable and portable. However, compared to laboratory instruments, portable non-destructive assays, critical assumptions which underlay quantification and interpretation differ. As archaeologists gather massive amounts of compositional and spectral data from materials like pottery, metals, soils, pigments, and glass, this abundance of data for analysis brings both opportunities and challenges. We discuss how to make this data meaningful, reproducible, and interoperable outside of laboratory contexts.

This session, organized by the Global pXRF Network (GopXRF.Net), invites contributions that explore the methodological, computational, and ethical frontiers of analytical data in chemical analysis in archaeometry. We welcome papers addressing workflows from data collection to interpretation, particularly those that integrate *Description* automation, machine learning, AI-based classification, or semantic modeling.

Our goal is to foster an open conversation on the future of chemical data in archaeological context that moves beyond the instrument—toward frameworks that are computationally robust, ethically grounded, and collaboratively reproducible.

Key themes for the session include:

- **AI and Machine Learning**  
Applications of supervised and unsupervised learning to characterize materials, detect anomalies, or predict provenance.  
Use of spectral fingerprinting and pattern recognition.
- **Automated Calibration and Standardisation**  
Inter-lab comparability and reproducibility.  
Advances in data and error handling.  
Development of open-source tools and calibration repositories.
- **Data Management, Semantics, and FAIR & CARE Principles**  
Structuring compositional data for long-term accessibility and reuse in data repositories in perpetuity.  
Ontologies and metadata standards for chemical data.  
First Nations Data sovereignty  
Critical perspectives on algorithmic bias and over-interpretation.
- **Case Studies**  
How integrated data approaches enhance understanding of technology, exchange, and provenance.  
Studies illustrating the full workflow from field collection to digital publication.

#### Audience and Impact:

This session is aimed at a diverse audience – archaeologists, archaeometrists, data scientists, and heritage professionals – who engage with chemical analysis, data modeling, or AI in archaeology. We hope to bridge gaps between field practitioners and computational modelers by showcasing both grounded case studies and conceptual frameworks.

#### Expected Outcomes:

Foster cross-disciplinary dialogue and community building.  
Identify bottlenecks in analytical workflows and share open solutions.  
Promote reproducible, ethical, and AI-ready data practices in archaeometry.  
Inspire collaboration through GopXRF.Net and related networks.

#### Future perspectives:

We also envision follow-up discussions (virtual or in-person) or the possibility of an open-access proceedings volume or workshop post-conference. The session will be structured to encourage dialogue, including a closing panel discussion.

|                      |                                                                                                                                                                                                                     |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:30 – 14:40</b> | Introduction and Welcome                                                                                                                                                                                            |
| <b>14:40 – 15:00</b> | 229. XRF as a Screening Tool for Diagenesis<br><i>Marian Hamilton (University of Northern Colorado); Cyler Conrad (Pacific Northwest National Laboratory); Lee Drake (University of New Mexico)</i>                 |
| <b>15:00 – 15:20</b> | 240. Inferring Environmental Processes using XRF<br><i>Lee Drake (University of New Mexico); Jenni DeGraffenried (Dugway Proving Ground); Andrea Brunelle (University of Utah); Isaac Hart (University of Utah)</i> |
| <b>15:20 – 15:40</b> | Coffee break                                                                                                                                                                                                        |
| <b>15:40 – 16:00</b> | 254. All Roads Lead to Accuracy? Navigating Calibrations and Coefficient Corrections in pXRF Studies<br><i>Michaela Schauer (VIAS/NHWW)</i>                                                                         |
| <b>16:00 – 16:20</b> | 158. Investigation of trade network using elemental analysis of transport amphoras with pXRF<br><i>Anno Hein (N.C.S.R. "Demokritos")</i>                                                                            |
| <b>16:20 – 16:40</b> | 323. Using p-XRF to distinguish archaeological pottery sherds found on Tami Island, Eastern Papua New Guinea                                                                                                        |



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*Kristine Hardy (ANU); Mathieu Leclerc (ANU)*

**16:40 – 17:00** 324. Getting to the Source: A New Approach to Using Provenancing to Explore People's Strategies of Stone Tool Making in the Deep Past at Pamwak Rockshelter, Papua New Guinea

*Caroline Spry (La Trobe University); Christina Pavlides (La Trobe University); Michelle Richards (The University of Melbourne)*

**17:00 – 17:20** 348. Is big-archaeo-geochemical data increasing our understanding of the past in Oceania?

*Michelle Richards (The University of Melbourne); Andrew McAlister (University of Auckland); Josh Emmitt (Auckland War Memorial Museum)*

**17:20 – 17:30** Break

**17:30 – 17:50** 359. Compatibility Challenges Between Quantitative Optical Emission Spectroscopy, and SEM-EDS in the Compositional Analysis of North Pontic Ancient Glass

*Anzhelika Kolesnychenko (The Cyprus Institute); Thilo Rehren (The Cyprus Institute)*

**17:50 – 18:10** 113. Rock Art Clustering Analysis for Group Identification Using Reflectance Spectroscopy (350-2500 nm) in La Pileta Cave (Málaga, Spain)

*Rubén Parrilla (ICArEHB); Sara Macías (Universidad de Sevilla); María Simón Vallejo (Universidad de Sevilla); Miguel Cortés Sánchez (Universidad de Sevilla)*

**18:10 – 18:30** 195. A Bayesian Multi-Endmember Mixing Framework for Lead Isotope Provenancing

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*Siran Liu (University of Science and Technology Beijing)*

**18:30 – 18:50** 58. An Explainable Multimodal Modelling Framework with Physics Constraints: A Case Study on Predicting the Degradation of Heritage Leather Materials

*Xinyi Lei\*; Can Liu (Sichuan University); Peng Zhao (Sichuan University); Xiyang Ma\*; Yuchuan Bai\*; Wenqiang Yang\**

*\* China National Shadow Puppetry Museum*

**18:50 – 19:10** 430. Beyond the Instruments: AI-Driven Integration of Multisensor Data in Archaeometry

*Martina Naso (University La Sapienza of Roma); Nevio Dubbini\*; Arthur Leck (Université Bordeaux Montaigne); Rémy Chapoulie (Université Bordeaux Montaigne); Gabriele Gattiglia\*; Claudia Sciuto\**

*\* University of Pisa*

**19:10 – 19:30** Discussion

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## 58. An Explainable Multimodal Modelling Framework with Physics Constraints: A Case Study on Predicting the Degradation of Heritage Leather Materials

*Xinyi Lei (China National Shadow Puppetry Museum)*

*Can Liu (Sichuan University)*

*Peng Zhao (Sichuan University)*

*Xiyang Ma (China National Shadow Puppetry Museum)*

*Yuchuan Bai (China National Shadow Puppetry Museum)*

*Wenqiang Yang (China National Shadow Puppetry Museum)*

### Introduction

An explainable multimodal neural framework is presented that enforces a hard, physics-based FTIR Amide I zero-sum conservation constraint, enabling physically credible degradation prediction under small-sample regimes. The present study focuses on rawhide “clean leather” (un-tanned hide) used in Chinese shadow puppetry, a proteinaceous heritage substrate that exhibits complex, nonlinear ageing responses to light, thermal, and chemical stressors. In such settings, data scarcity and batch heterogeneity often limit purely data-driven models, while conservation decision-making requires interpretable predictions grounded in molecular constraints. In archaeological contexts, comparable protein-based artefacts are further challenged by burial environments, chemical corrosion, and post-excavation light/thermal shocks, making physics-consistent prediction important for defining handling and exhibition limits and prioritising stabilisation immediately after recovery. Methodologically, a structure-level hard constraint is embedded to enforce zero-sum behaviour across Amide I subcomponents ( $\alpha$ -helix,  $\beta$ -sheet,  $\beta$ -turn, random coil), fundamentally differing from soft penalties or post hoc projection and thereby preventing physically impossible outputs. Although validation in this study is restricted to shadow-puppet rawhide, the modelling principle is potentially transferable to other proteinaceous heritage materials

(e.g., parchment or silk) by re-training on material-specific datasets and adapting Amide I component definitions.

### Methods and Materials

#### Dataset and ageing design

A 520-sample corpus of rawhide (Shadow Puppet Leather) was compiled under single-factor accelerated ageing: (i) UV-A centred LED irradiation with controlled irradiance ( $25\text{--}100\ \mu\text{W}\cdot\text{cm}^{-2}$ ); (ii) forced-air thermal ageing ( $50\text{--}120\ ^\circ\text{C}$ ); and (iii) chemical immersion spanning acids, bases, salts, and oxidants across 10 concentration and 10 duration levels. “Museum-like” storage provided a slow-change baseline. For each sample, pre/post mass, geometry, RGB colourimetry, and ATR-FTIR spectra ( $4000\text{--}650\ \text{cm}^{-1}$ ) were recorded, quantifying Amide I sub-bands into  $\alpha$ -helix,  $\beta$ -sheet,  $\beta$ -turn, random coil via second-derivative deconvolution and curve fitting (sub-fractions sum to 1).

#### Inputs and targets

Model inputs comprise (a) initial state (mass, size, colour, FTIR fractions); (b) exposure descriptors (ageing type; UV irradiance and duration; temperature and duration; chemical type, concentration and duration). Targets include  $\Delta\text{mass}/\Delta\text{size}$ ,  $\Delta R/\Delta G/\Delta B$ , and  $\Delta\text{FTIR}$  sub-fractions.

#### Model

The PCNN implements a lightweight sequence-style embedding (LSTM) to aggregate ordered “condition→response” segments, plus multi-head attention to modulate contributions from light/thermal/chemical channels for interpretability. Crucially, a hard physics layer outputs three FTIR deltas ( $\Delta\alpha$ -helix,  $\Delta\beta$ -sheet,  $\Delta\beta$ -turn) and derives  $\Delta\text{random} = -(\Delta\alpha + \Delta\beta\text{-sheet} + \Delta\beta\text{-turn})$ , enforcing exact zero-sum at any input. A HybridLoss (per-output weighting) balances optical/physical targets with FTIR structure changes, prioritising physically meaningful outputs. Training uses standardisation for continuous inputs; models are evaluated under (1) single random split and (2) GroupK-Fold by batch to prevent leakage across batches (Hochreiter and

Schmidhuber 1997; Raissi, Perdikaris, and Karniadakis 2019). A controlled ablation toggled physics (on/off), attention (on/off), backbone (LSTM vs. MLP), and loss (Hybrid vs. MSE), with all else fixed and evaluation under a single random split and GroupKFold.

#### Metrics and physics consistency

Reported metrics include  $R^2$ , NRMSE, and a conservation error (mean absolute deviation of the FTIR four-term sum from zero). SHAP and attention maps support interpretability.

### Results

#### Small-sample feasibility

Under a single random split (an optimistic small-sample scenario), PCNN achieved  $R^2 \approx 0.79$  and NRMSE  $\approx 0.09$  across targets.

#### Cross-batch generalisation with physics on

With GroupKFold (by BatchID) and physics enabled,  $R^2 = 0.506$  and NRMSE = 0.111 were obtained with zero-sum strictly satisfied (conservation error  $\approx 0$ ), yielding a conservative cross-batch estimate aligned with curatorial needs where reliability and physical plausibility outweigh over-fitting.

#### Trade-off without physics

Disabling the constraint improves surface metrics (e.g.,  $R^2 \approx 0.80$ , NRMSE  $\approx 0.073$  in random splits) but incurs FTIR conservation violations ( $\sim 0.45\%$  typical), undermining molecular-level credibility. For decision support, Physics = ON is recommended as the primary reporting mode.

#### Ablation results

Ablation confirms a precision–consistency trade-off: physics-off raises  $R^2$ /lowers NRMSE but violates Amide I zero-sum ( $\sim 0.45\text{--}0.80\%$ ); physics-on slightly reduces accuracy yet enforces  $\sim 0\%$  conservation. Attention yields marginal gains but aids interpretation; LSTM > MLP as a compact sequence

aggregator; HybridLoss best balances error and physical fidelity. Compared with physics-off, the framework reduces the “physical impossibility” error from  $\sim 0.45\%$  to  $\sim 0\%$  with only modest accuracy loss.

#### Drivers of change

SHAP and attention indicate chemical stress as the dominant driver, with non-linear contributions from light and thermal variables;  $\beta$ -sheet responses suggest potential U-shaped thermal sensitivity, motivating tight temperature stability.

### Discussion and Broader Implications

#### Scientific significance

Embedding a hard constraint into a multimodal learner reconciles accuracy with molecular plausibility, a cornerstone for actionable heritage science in small-sample contexts where physics guidance regularises the hypothesis space and reduces spurious fits.

#### Methodological transparency

SHAP and attention provide audit trails linking predicted deterioration to exposure parameters and initial states; the explicit zero-sum guarantee respects established Amide I compositional relationships during protein denaturation/reorganisation.

#### Policy and preventive conservation

Findings support priority control of chemical pollutants, instantaneous light-level limits, and tight thermal stability to avoid threshold effects; even under stricter cross-batch protocols, physics-consistent outputs remain operationally trustworthy for risk triage and scenario testing.

Archaeological implications

The PCNN offers concrete benefits for archaeological practice by enabling small-sample, non-destructive prediction of multi-scale deterioration from routinely acquired signals such as ATR-FTIR, colour, and mass/geometry, which is particularly valuable when only tiny or fragile fragments are available. Through physics-consistent auditability—implemented via a hard Amide-I zero-sum constraint together with SHAP and attention analyses—the model links predicted changes to agents typical of burial and post-excavation contexts, especially chemical pollutants, instantaneous light spikes, and thermal shocks, thereby functioning as a defensible decision-support tool. Beyond interpretation, the framework supports actionable limits and scenario testing: it informs immediate post-recovery light-level caps, prioritises pollutant control (e.g., acids, bases, chlorides, and oxidants), and motivates tight temperature stability to avoid  $\beta$ -sheet U-shaped responses. Importantly, the same modelling strategy is readily transferable to other proteinaceous heritage substrates, including parchment and silk. In short, this framework translates multi-modal sensor data into actionable, physics-consistent preservation guidelines, offering archaeologists a defensible tool for safeguarding irreplaceable materials from the moment of excavation.

Transferability

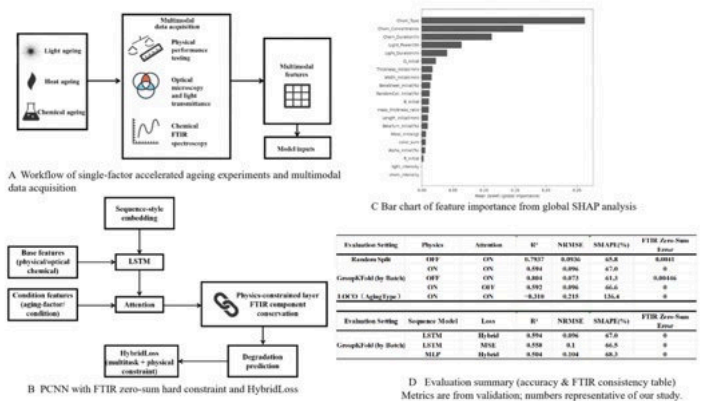
The architecture is material-agnostic across proteinaceous substrates: by swapping training data and re-tuning FTIR segmentation, the same constraint layer and loss can model parchment and silk, where Amide I transitions likewise reflect degradation chemistry.

Limitations and next steps

Under LOCO evaluation, withholding Light produces the largest shift, whereas Chemical and Thermal are comparatively more stable, reflecting data imbalance rather than methodological failure. Despite reduced accuracy under strict extrapolation, the zero-sum constraint remains satisfied.

These results highlight the need for balanced sampling and provenance-aware metadata—particularly for light exposure histories—and motivate future work on Light subset expansion, multi-factor coupling (light–heat–chemistry), and transfer learning to improve robustness and portability.

Figure 1. Overview and key results: A) Workflow of single-factor accelerated ageing experiments and multimodal data acquisition; B) PCNN with FTIR zero-sum hard constraint and HybridLoss; C) Bar chart of feature importance from global SHAP analysis; D) Evaluation summary (accuracy and FTIR consistency table).



References

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### 113. Rock Art Clustering Analysis for Group Identification Using Reflectance Spectroscopy (350-2500 nm) in La Pileta Cave (Málaga, Spain)

*Rubén Parrilla (ICArEHB)*

*Sara Macías (Universidad de Sevilla)*

*María Simón Vallejo (Universidad de Sevilla)*

*Miguel Cortés Sánchez (Universidad de Sevilla)*

Portable archaeometric techniques have become common in archaeological research over the past two decades, specifically with atomic emission and molecular vibration methods for field contexts. Less attention has been paid to simpler spectroscopic approaches, particularly visible and infrared reflectance spectroscopy, despite their potential for rock art analysis when linked to machine learning methods.

This research tests whether reflectance spectroscopy paired with clustering methods can distinguish compositional groups among rock art motifs, offering a non-destructive means to examine chronological and stylistic relationships through pigment composition. Data has been acquired in La Pileta Cave in Málaga, Spain, which preserves 1236 catalogued motifs, including 872 attributed to the Paleolithic. The cave's artistic record spans roughly 30,000 years, from the Upper Paleolithic into the Bronze Age, and recent work suggests some assemblages may date to even earlier Upper Paleolithic phases in the region.

We collected 235 spectral measurements from motifs in different areas of La Pileta Cave using an ASD TerraSpec Halo spectrometer (350-2500 nm range). The sample includes motifs from various periods, colors, and styles. Because cave surfaces often have calcite deposits and other alterations that complicate analysis (Jal et al. 2025), we compared different preprocessing workflows to identify which approaches work best in these conditions.

Preprocessing steps drew on methods from hyperspectral imaging research (Witteveen et al. 2022) and included spectral transformations, baseline corrections, and normalization. We reduced dimensionality before clustering to handle the high number of spectral variables, then tested several clustering algorithms—k-means, hierarchical clustering, and DBSCAN—following established practices for spectral data (Cruse et al 2021). We validated clusters by comparing them against existing chronotypological classifications, checking whether motifs from the same period grouped together statistically.

Motifs from related chronotypological horizons showed greater spectral similarity than motifs from different periods. This pattern held across multiple preprocessing and clustering combinations, though results varied with method choice. The data confirm that machine learning methods for reflectance spectroscopy can separate compositional groups linked to different artistic phases. These patterns also suggest a way forward for motifs that lack clear typological features: their spectral profiles can be compared to established reference groups to propose chronological or stylistic assignments based on compositional similarity.

These preliminary results show that reflectance spectroscopy has practical value for rock art research in caves, where preservation conditions limit other approaches. The match between spectral clusters and known chronologies indicates that pigment composition tracks temporal and cultural differences. This matters for sites where dating is not possible and typology can't be analyzed. Building spectral reference libraries from well-characterized motifs creates a basis for assigning undated or ambiguous rock art to particular horizons. This compositional approach offers a practical alternative for chronocultural associations. Combining portable spectroscopy with statistical analysis provides a method that is both scalable and reproducible, without compromising rock art preservation.

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## 158. Investigation of trade network using elemental analysis of transport amphoras with pXRF

Anno Hein (N.C.S.R. "Demokritos")

The compositional differences of archaeological ceramics manufactured at different production sites are basically related to the chaîne opératoire exploiting geochemically diverse raw material sources and preparing the clay paste following to a particular recipe by refinement, tempering and/or mixing of the initial raw materials. The elemental composition of the ceramics is commonly examined with laboratory methods, such as NAA, ICP-MS or WD-XRF providing high analytical performance in terms of precision and accuracy. However, for laboratory analyses sampling of ceramic fragments or even entire vessels is necessary, which in the case of archaeological artefacts is not always possible. During the last 20 years, though, the use of handheld

portable energy dispersive XRF (pXRF) systems became common for the elemental analysis of archaeological artefacts as it facilitates in fact non-invasive in-situ analysis. Apart from this, pXRF is a comparably fast analytical method providing prompt results and allowing for large numbers of measurements within short time periods. For this, it can be used for example as an initial analytical method for examining large assemblages in view of optimizing the sampling strategy for laboratory analysis. On the other hand, particularly in the case of ceramic analyses there are several drawbacks regarding the use of pXRF. It is extremely surface sensitive, provides a limited number of element concentrations and the analytical performance is lower in comparison with laboratory methods. Particularly, the lower precision introduces additional variation to the determined elemental compositions and thus impedes the statistical evaluation of the pXRF data following established approaches of multivariate statistics, which are commonly applied to data collected in laboratory analyses.

During the recent years a large number of pXRF data have been collected in manufacturing and trading centres of Archaic, Hellenistic and Roman transport amphorae from the Eastern Aegean region providing potential insights in the trade networks during these periods. Within diverse projects, pXRF was indeed initially applied following the above-mentioned approach for optimizing the sampling strategy. Based on NAA of a considerable part of the samples distinct compositional categories could be defined in the amphora assemblages assumedly representing individual production centres. These categories can be used for predefined categorization of pXRF data in supervised machine learning models, which then can be used for categorical prediction of pXRF data of fragments, which were not analysed by NAA. Various machine learning models, such as support vector machines (SVM), random forests (RF) and supervised artificial neural networks (ANN), have been tested for the automated categorization of elemental compositions based on the pXRF data of the transport amphorae. However, the training dataset was unbalanced concerning the number of samples per category and the number of data records with several hundreds of elemental compositions was still



inadequate for training supervised ANN. For this, synthetic training data sets were generated, for example based on the covariance matrices of the individual categories. Even though amphoras of unknown origin can only be assigned to categories incorporated in the present machine learning models. However, the ML models always can be extended towards incorporating additional categories in order to build up an expert system for the identification of the origin of manufacture.

## 195. A Bayesian Multi-Endmember Mixing Framework for Lead Isotope Provenancing

*Siran Liu (University of Science and Technology Beijing)*

Archaeometallurgists have employed lead isotope analysis (LIA) to investigate the provenance of bronze artefacts for more than four decades. Among the four naturally occurring isotopes of lead,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ , and  $^{208}\text{Pb}$  are radiogenic, whereas  $^{204}\text{Pb}$  is non-radiogenic. Ratios between these isotopes (e.g.  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ , and  $^{208}\text{Pb}/^{204}\text{Pb}$ ) vary systematically among geological deposits as a function of their formation age and source materials. Because isotopic fractionation during pyrometallurgical processes is negligible, these ratios provide a robust geochemical tracer for the copper and lead used in bronze production. To date, more than 10,000 lead isotope measurements have been published worldwide, and this number continues to increase rapidly.

Despite its success, the expansion of LIA datasets has exposed fundamental methodological challenges, the most significant of which is the mixing effect. Unlike stone or ceramic materials, metals can be repeatedly melted, recycled, and combined from multiple sources. As a result, the isotopic composition of an artefact represents a convex combination of its contributing sources and will rarely coincide with any single ore deposit. This phenomenon is difficult to address using traditional LIA approaches, which typically rely on point-to-point matching between artefacts and ore samples across

the three isotope ratios. Such methods perform poorly when mixing is present. Classical linear mixing models, for example, regression of  $^{206}\text{Pb}/^{204}\text{Pb}$  against the reciprocal of lead concentration, can be effective in simple two-endmember systems, but they neglect geological variability within endmembers and do not generalise to scenarios involving multiple sources.

To address these limitations, we present a Bayesian multi-endmember mixing model that adapts and extends the MixSIAR framework for application to LIA. The model explicitly incorporates within-source isotopic variance and analytical uncertainty for multiple candidate ore groups, and it returns full posterior distributions for the proportional contribution of each source to each artefact. This structure enables principled propagation of uncertainty into subsequent analyses. To define geologically meaningful sources, we compiled lead isotope data from 319 copper and lead mines across China and applied dimensionality reduction using UMAP, followed by clustering to identify five endmembers (A–E), each broadly corresponding to a major geographic region.

We apply this framework to more than 500 bronze artefacts from 19 archaeological sites dated to the Middle Spring and Autumn period (MSA; 650–570 BCE), a critical phase of political transformation in early Chinese history. Following the decline of centralized Zhou authority at the end of the Western Zhou period (8th century BCE), the political landscape was reshaped by continuous competition among regional states. During the MSA, an alliance of Central Plain states coalesced around the powerful state of Jin to counter the expansion of Chu in the south, which had drawn many southern Central Plain polities away from allegiance to the Zhou court. This rivalry drove a series of political and fiscal reforms, and control over metal supply networks became increasingly strategic for both blocs. Lead isotope data from bronze artefacts of this period reveal complex patterns of metal mixing. Posterior source contribution profiles indicate pronounced site-specific variability. By applying Brainerd–Robinson similarity to the five-endmember contribution vectors, we constructed an inter-site interaction network; Louvain community detection identifies modules that closely mirror the contemporaneous political landscape. Notably, the northern state of Jin and the southern state of Chu

exhibit weak connectivity, whereas Qin, an ally of Chu, appears deeply embedded within Chu-associated circulation networks, despite the geographic barrier imposed by the Qinling Mountains.

These results demonstrate that an uncertainty-aware, mixing-explicit approach to lead isotope analysis can provide new insights into ancient metal supply systems and their political economies. By moving beyond brittle one-to-one provenance matching, this framework enables more robust inference about resource flows and the sociopolitical structures that shaped them.

## 229. XRF as a Screening Tool for Diagenesis

*Marian Hamilton (University of Northern Colorado)*

*Cyler Conrad (Pacific Northwest National Laboratory)*

*Lee Drake (University of New Mexico)*

Portable X-ray fluorescence spectrometry (pXRF) is an increasingly powerful tool for non-destructive qualitative and quantitative analysis of elemental compositions across a wide range of disciplines, including art history, archaeology, and materials science. In paleontological and archaeological research, pXRF has been employed to reconstruct ancient diets and habitats, distinguish fossil bone from surrounding matrix, identify specimen provenance, and assess the degree of organic preservation. Building on these applications, this study explores a new use for pXRF: as a rapid, non-destructive screening method to evaluate the degree of diagenetic alteration in biogenic materials prior to more costly or destructive analytical approaches.

We demonstrate this application using two case studies: (1) a collection of nineteenth-century coffee beans excavated from a Gold Rush-era archaeological site near San Francisco, California, USA, and (2) fossilized North American primate teeth dating to the Paleocene and Eocene housed in the University of Wyoming's Geological Museum. In both cases, elemental concentrations were measured using photon counts on a Bruker 5g handheld XRF.

Elemental counts were normalized to calcium ( $(\text{element}/\text{Ca}) \times 1000$ ). These values were then compared to maximum threshold concentration (MTC) values, calculated as the average calcium-normalized elemental concentration of modern, unaltered samples, plus two standard deviations. Samples in which elemental values exceeded the modern mean MTC were flagged as exhibiting potential diagenetic alteration.

To validate this approach, a subset of the archaeological coffee beans was independently analyzed using inductively coupled plasma mass spectrometry (ICP-MS) for trace element composition. ICP-MS results indicate that the beans are heavily diagenetically altered, consistent with the pXRF-based MTC results. This concordance suggests that handheld XRF can effectively identify post-depositional chemical modification, even in delicate or organic-rich archaeological materials. In contrast, application of the same method to the fossil primate teeth revealed elemental patterns and Ca/P ratios consistent with minimal diagenetic change, aligning with prior studies demonstrating that Ca/P ratios derived from pXRF can serve as a reliable proxy for preservation state.

Together, these results illustrate that handheld XRF can serve as a practical and reliable frontline screening tool for detecting diagenetic alteration across diverse material types. By providing rapid, in situ elemental data, pXRF enables researchers to triage specimens before committing to destructive analyses such as stable isotope or trace element measurements. This approach enhances analytical efficiency, reduces sample loss, and increases confidence in subsequent geochemical or isotopic interpretations. The method's portability and non-destructive nature make it particularly well suited for field contexts and museum collections, where conservation concerns often limit sampling. More broadly, integrating handheld XRF screening into archaeological and paleontological workflows has the potential to streamline research pipelines and refine our understanding of ancient biological and environmental systems through more targeted, preservation-aware sampling strategies.

## 240. Inferring Environmental Processes using XRF

*Lee Drake (University of New Mexico)*

*Jenni DeGraffenried (Dugway Proving Ground)*

*Andrea Brunelle (University of Utah)*

*Isaac Hart (University of Utah)*

XRF is most prominently used in compositional analysis and provenance studies in archaeology. However, the data produced using XRF can also be insightful into chemical processes which underly the formation environment of sediments. Here we present the results from three sedimentary cores from Dugway Proving Grounds (DPG) which document significant environmental and climate change from 30,000 cal yrs BP.

Following 2mm scans across three cores, the longest being 5 meters, we document the following processes:

- 1) Detrital inputs washing in from riverine inputs which document shifts in the polar jet stream during the last glacial maximum (LGM)
- 2) The discrete impacts of individual Heinrich events (HE) on climate in the region
- 3) The massive outflows from the Bonneville flood at 17,800 - 17,500 cal yr BP
- 4) A short lived hypoxic period during the stabilized post-flood lake level,
- 5) A significant evaporative event during the Bølling-Allerød which marks the end of the lake record,
- 6) The transition of the environment from a lake to a drylands playa to a spring
- 7) The connection between spring activity and human occupation in the region

While climatic and environmental trends are the focus of this talk, we also highlight how the elemental ratios used to interpret these processes can be useful to provenance studies; ceramic clays are produced via sediment deposition and the nature of their deposition is what ultimately leaves provenance markers in their geochemistry.

## 254. All Roads Lead to Accuracy? Navigating Calibrations and Coefficient Corrections in pXRF Studies

*Michaela Schauer (VIAS/NHMMW)*

In portable X-Ray Fluorescence (pXRF) research, accuracy is widely recognised as a key objective for producing scientifically valid chemical data. Two approaches are commonly used to achieve this: calibration and coefficient corrections. Both aim to improve the agreement between instrument output and reference values—typically obtained from established laboratory methods such as NAA, ICP-MS or WD-XRF and referred to as accepted reference values or true values. Both are most effective when applied to well-characterised sample sets covering a broad spectrum of potential chemical concentrations for each element in question. Each sample set must reflect the materials and contexts in which the calibration or coefficient correction will later be applied – pottery samples for ceramic materials, metal samples for metal analyses, and so on. Both approaches therefore require thoughtful sample selection, awareness of material variability, and consistency in measurement protocols not only for the laboratory analysis but also for pXRF. Despite their shared goal, calibrations and coefficient corrections operate through distinct mechanisms and benefit from clearer differentiation in terminology and application.

Calibration refers to the correction of raw spectral data by modelling the relationship between instrument signal and known elemental concentrations. It addresses influences such as elemental interferences and peak overlaps,

which are particularly critical for calibration quality, alongside the choice of normalisation procedure (e.g. time, counts, ROI) and regression model (e.g. linear, non-linear, Lucas-Tooth). Outlier exclusion is generally of lesser importance in calibration workflows.

Coefficient corrections – also described as type standardisation, user factors, secondary calibration, calibration correction, or post-processed slope correction – are nearly exclusively based on linear regressions (either through the origin or with intercept) between analytical data generated by the instrument's software (based on predefined settings such as TestAllGeo, Mudrock-Dual, or GeoChem) and the accepted reference values. In this approach, improving the correction typically involves the exclusion of outliers, making the selection and justification of the sample set especially important.

Calibration requires deeper knowledge of X-ray fluorescence physics and the underlying chemistry of the materials being analysed, as well as an understanding of the mechanics of different normalisation strategies and statistical algorithms applied. Coefficient corrections are easier to apply but demand a thorough understanding of the sample set. Removing an outlier must be carefully considered and clearly justified, as it may reflect meaningful material characteristics – such as distinct geological origin, preparation technique, or formation conditions – that challenge the assumptions underlying the manufacturer's measurement mode calculations. For instance, a sample formed under anoxic conditions may appear as an outlier but still provide valuable information about the origin of objects as well as the analytical system's limitations or behaviour.

As highlighted in recent literature, the establishment of clear definitions and appropriate use cases for both calibration and coefficient corrections is essential to improving methodological clarity across the field. Recent work has started to define quantitative benchmarks for evaluating the robustness of coefficient corrections, including  $r^2$ , the relative standard error of the estimate (rSEE), and bootstrap confidence intervals. These metrics support more

transparent and reproducible applications of linear corrections. Their integration into workflows – such as those outlined in the Munich Procedure, an open-source R code – marks a key step toward standardising the evaluation of empirical correction strategies. In parallel, open-source tools like CloudCal by Lee Drake offer cloud-based platforms for calibration, reflecting growing interest in open, well-documented solutions for independently calibrating pXRF instruments in heritage science.

For these tools to be practically usable and widely adopted, they must be accompanied by clear documentation and application examples tailored to real-world use cases. Only with this support can users apply these workflows correctly and confidently. As ongoing efforts to automate both calibration and coefficient correction workflows gain traction, the need for transparency, robust guidance, and accessible examples becomes even more critical.

In light of these developments, this presentation outlines the distinct approaches of the two pathways to accuracy – calibration and coefficient corrections – not only from a user perspective. It will guide through the application of both methods using a well-established standard set of archaeological pottery hosted by Dr. Markus Helfert at the Frankfurt Pottery Laboratory, highlighting the critical differences in the decision-making processes behind creating calibrations and coefficient corrections. The quality of the resulting models will be assessed based on the benchmarking criteria defined in the Munich Procedure, with attention to the conclusions that can be drawn for broader community practice. By comparing these approaches and their implementation in a real-world case study, this contribution directly supports the aim of advancing reliability of chemical data in archaeometry.

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### 323. Using p-XRF to distinguish archaeological pottery sherds found on Tami Island, Eastern Papua New Guinea

*Kristine Hardy (ANU)*

*Mathieu Leclerc (ANU)*

Portable X-Ray Fluorescence (p-XRF) can be used to determine the geochemical signatures of archaeological ceramics. It is useful for distinguishing which pottery sherds are likely to derive from vessels made with materials from the same geological area. While there have been concerns expressed about its ability to measure signatures in heterogeneous earthenware, it has proven successful in differentiating between sherds from vessels created in different regions, including distinguishing between sherds from the vessels made in the Eastern Highlands and Markham Valley regions of Eastern Papua New Guinea (PNG). In this study we used it to group archived pottery sherd offcuts originating from sherds collected as surface finds on Tami Island off the eastern coast of PNG in 1969 (Abramson 1969).

Tami Island was a trade centre for Eastern PNG and Western New Britain. The islanders specialised in woodwork carving and did not produce ceramics. The earliest known pottery sherds in PNG have been dated to around 3300BP and it is thought to have been introduced to the region by Austronesian migrants. In the Morobe and Madang regions of Eastern PNG pot making was practiced by several communities, using different building and decorating

techniques, by 300BP. These communities include several Austronesian Oceanic speaking communities in the Markham Valley.

p-XRF and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) have previously been used to define geochemical signatures for Markham Valley pottery exported east to the Eastern Highlands. Several of the Tami Island sherds have forms and decoration indicative of Markham Valley vessels. Others appear to have derived from Madang and Sio pottery. Some sherds have characteristics of the Type X pottery, dated to 1000-500 BP and proposed to be one of the few have grog tempered potteries of the Pacific (Lilley and Specht 2007).

To determine if any of the Tami sherds had similar geochemical signatures to the published Markham Valley signature, we used the Bruker Tracer 5i with three different voltage/filter combinations and reference standards (including Ohio Clay, NIST679 Brick Clay and fifteen inhouse pelleted ceramic standards). A critique of the use of p-XRF for earthenware studies has been that the heterogeneous nature of earthenware may produce variable readings. However, we have found that triplicate readings are nearly always very similar, even with the use of the 3mm collimator. Values from the 8mm and 3mm collimators (once normalised) were similar but some sherd offcuts could only be measured with the 3mm due to their thinness. The sherd core was always measured. Spectra were background (escape) corrected and deconvoluted with 10 stripping cycles using the ARTAX software. Parts per million (PPM) values were obtained from standard curves constructed with the reference standards.

Hierarchical clustering was undertaken on the Log2 values using the Canberra distance metric in the tidyheatmap R library (Engler 2025). In bioinformatic studies of gene expression, the dendrograms of clustered values are usually accompanied by heatmaps showing values coloured by their z-score. The R package pheatmap and several packages that build upon it, are commonly used. The tidyheatmap library adapts pheatmap for use with 'tidy' formatted data. This type of visualisation allows viewers to easily see the elemental signatures associated with different clusters (Figure 1).

Examination of the iron (Fe), chromium (Cr), cobalt (Co), magnesium (Mg) and calcium (Ca) levels shows that 11 of the 74 Tami sherds have values within the ranges reported for Adzera made pottery from the Markham Valley. This includes TAMI10 which has Markham Valley decoration and form characteristics. The values for TAMI9 and TAMI12, which have Markham Valley decoration/form do not fall within the ranges and may derive from a different area of the Valley. In recent times there were multiple clay sources utilised, and oral histories indicate past community movements.

The dendrogram of the values shows the sherds with macroscopic calcareous appearance clustering together with a high Ca signature (Figure 1). These include the red-slipped sherds with everted rims, features typical of Madang pottery.

By comparing the sherd morphological features, p-XRF signatures and the available petrography, we can propose origins for the different pottery that found its way to Tami Island. The p-XRF technique works well on small pottery fragments (including those with visible inclusions), is non-destructive and can efficiently analyse large numbers of samples. Visualisation with (z-score) heatmaps is a useful way to associate element signatures with clusters.

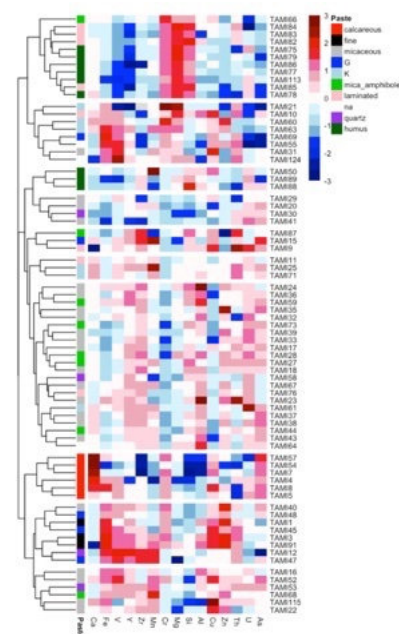


Figure 1: Visualisation of the geochemical signatures of sherds found on Tami Island. The element levels are coloured according to the z-scores of their Log2 values. Colours on the left side show the original macroscopic paste classifications. The Canberra distance metric was used for clustering on the sherds. Clustering and visualisation performed with the tidyheatmaps R library.

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## 324. Getting to the Source: A New Approach to Using Provenancing to Explore People’s Strategies of Stone Tool Making in the Deep Past at Pamwak Rockshelter, Papua New Guinea

*Caroline Spry (La Trobe University)*

*Christina Pavlides (La Trobe University)*

*Michelle Richards (The University of Melbourne)*

### Introduction

Advances in techniques for identifying the discrete sources where people procured stone for tool making (sourcing) have fundamentally transformed what we can learn about change and resilience. However, sourcing studies to date have been limited to investigating people’s movement across the landscape to obtain stone material, and whether people traded and exchanged stone material with neighbouring groups. Here we present a new approach that uses sourcing to more closely examine how people made and used stone tools in the deep past. We discuss a case study from Pamwak Rockshelter, Papua New Guinea, where pXRF has enabled investigation of potential stone knapping episodes and strategies of stone tool making that are unique to specific sources of obsidian.

### Methods and materials

We analysed c. 300 obsidian (including weathered obsidian and ‘pitchstone’) artefacts dated to ~15-7 ka cal BP (Roberts et al. 2022). The obsidian artefacts were excavated from 4 squares in Pamwak Rockshelter in 1980s by Clayton Fredericksen, Matthew Spriggs and Wal Ambrose in 1989 – 1990 (Fredericksen et al. 1993).

Geochemical analysis was conducted using an Olympus Delta pXRF and the data was corrected using PYRO and MURR obsidian standards (Frahm 2019; Glasscock 2020). We compared our data set to the published reference data sets available from Summerhayes et al. (2014) and the POFATU database (Hermann et al. 2020). Bivariate scatter plots of trace and major elements were used to identify geological sources and match artefacts (McAlister 2019; Richards 2019). Technological analyses looked for regional variation (Pavlides and Kennedy 2007) and conjoins and refits within stratigraphic units (Foley et al. 2017; Spry and Stern 2016).

### Results

Two known sources and four unknown sources of obsidian were identified using element bivariate scatter plots (e.g. Rb/Sr and PWF Zr/TiO<sub>2</sub> / Nb/Y). One on-island NW Manus source was grouped out clearly from the known off-island St Andrews Strait source and four unknown sources. The unknown sources group more closely to the St Andrews Strait source, suggesting these sources are also off-island sources.

This sourcing analysis allowed us to analyse the on-island NW Manus technology which showed core preparation and standardised flake production on Kombewa flakes both rounded and elongated. The on-island artefacts were less intensively retouched which is somewhat expected given the proximity to the local material source, but may also be indicative of the raw material properties. In contrast, the off-island St Andrews Strait and other unknown sources technology showed core preparation, flake and tools with recurring features (standardisation) and more intensive retouching of this distant material and may indicate a level of recycling or the use of the site as a secondary obsidian source.

### Discussion

This study demonstrates the usefulness of a new application for geochemical sourcing to develop more nuanced understanding of stone tool technology (source groups, knapping groups, refits). It can help us understand how people in different social or cultural groups used the obsidian sources within

their proximity and how the obsidian characteristics influence stone tool technology, but also how different flaking strategies used by people are particular to sources. The technology and tools made can be investigated further with usewear and residue analyses to confirm their functions.

We will continue to work with Mr Poyap Ponau and Juliane Boettger on Manus Island, re-connecting with local communities and interpreting heritage and the past together. Manus locals are interested in the deep past and the history of archaeology, especially uncovering the contribution of local people to past archaeology projects from the 1980s.

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### 348. Is big-archaeo-geochemical data increasing our understanding of the past in Oceania?

*Michelle Richards (The University of Melbourne)*

*Andrew McAlister (University of Auckland)*

*Josh Emmitt (Auckland War Memorial Museum)*

#### Introduction

Almost thirty years ago, there were great calls for an archaeological geochemical database in the Pacific as well as calls for sourcing protocols and reporting standards (Sinton and Sinoto 1997; Wiesler and Sinton 1997). These calls were based on key archaeological questions of the time, namely understanding past long-distance interaction across Polynesian and within island groups (Wiesler and Sinton 1997). Certainly, these research questions remain important in Pacific archaeology today.

The Pofatu database, an open-access database for geochemical sourcing of archaeological materials, was launched in 2020 (Hermann et al. 2020). Since then, it has been cited in 11 research articles (Google Scholar metrics 2025). Yet, while these publications cite the existence of Pofatu the majority have not used the geochemical data held in Pofatu in their research.

To ameliorate this, we examine the contents of Pofatu and suggest ways for researchers and Pasifika communities to better engage with cultural heritage databases. There are now many meta-tools (machine learning and AI) available or bespoke tools, which can be designed for specific research questions. Critically, while Pofatu follows the FAIR principles, more work towards the CARE principles would also be worthwhile.

#### Methods and materials

Statistical analyses of the Pofatu database metadata and chemical data were used to evaluate the database contents. The Pofatu database encourages contributions from researchers and is continually growing. At its release in

2020, it included over 7700 samples, which has since more than doubled to currently (October 2025) include data for almost 17,000 specimens.

#### Results

##### -Geographic coverage

The Pofatu database is focused on the Pacific region. Within that region, the majority of samples (over 70%) are from East Polynesia, reflecting several studies targeted at identifying and characterising both artefacts and sources of tool stone in that region. Other regions include West Polynesia (8%), Melanesia (18.7%) and Maritime Southeast Asia (0.7%). Approximately two-thirds of the database samples are artefacts, while one-third are reference samples collected from quarries and other source locations.

##### -Techniques and instrumentation

A variety of techniques and instrumentation has been employed by different researchers. Portable handheld XRF (pXRF) instruments have been by far the most popular, accounting for over half of the total. This is likely because of the technique's low cost, widespread availability to archaeological researchers, and ability to perform non-destructive analyses. It is difficult to associate specific instruments with each analysis because multiple instruments have been used for some studies. However, a summary of the research indicates that Bruker and Innov-X handheld XRF instruments are the most common. Desktop ED-XRF has been commonly used non-destructively in the Pacific, and almost one-third of the samples in the database have used this method. The remaining 15% of the database were analysed using destructive techniques, including WD-XRF, ICP-MS and ICP-AES.

##### -Element representation

Element representation is quite varied, reflecting the number of different analytical methods used. The five "mid-z" elements (Rb, Sr, Y, Zr & Nb) are included in almost all of the samples, while the major element oxides occur

in just under half of the total. Isotopes have also been reported for Pacific stone tools and sources, but their use has been limited to date.

#### -Materials

The materials in the Pofatu database include a variety of rock types that were used to manufacture tools. Rock types are specified for around half of the samples in the database. Volcanic glasses, including obsidians and pitchstones, are the most numerous, followed by other fine-grained volcanic stones, mainly basalts. Although almost half of the samples in the database do not have a rock type specified in Pofatu, more details are usually recorded in the primary sources.

#### Discussion

Based on our preliminary results it is possible to suggest several ways forward. As Wiesler and Sinton (1997) highlighted, protocols for sourcing, and likewise protocols for data repositories, could still be better established. Our analysis has identified that the inclusion of more complete geochemical datasets including major and trace elements (i.e. not just the elements used in the publication results) would greatly improve compositional analyses at regional scales. Geographic representation can be improved with more research as well as identifying gaps through data visualisation and mapping. In addition, geochemical databases aimed at geological studies, such as GeoRoc (Lehnert et al. 2000), can be incorporated into source datasets for locations that are not well represented by archaeological studies.

The various geochemical analytical techniques may be ranked for accuracy and precision so that the corresponding data might be corrected or used more appropriately in machine learning or AI models. Lastly, Pofatu contains only stone artefacts but there is great potential to include other archaeological materials, such as ceramics, coral, and bone and shell artefacts, especially for building isotopic maps.

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### 359. Compatibility Challenges Between Quantitative Optical Emission Spectroscopy, and SEM-EDS in the Compositional Analysis of North Pontic Ancient Glass

*Anzhelika Kolesnychenko (The Cyprus Institute)*

*Thilo Rehren (The Cyprus Institute)*

#### Introduction

In the 1980s, more than 700 samples from Bronze and Iron Age contexts in the North Pontic region were analyzed by V. A. Galibin at the Laboratory of

the Institute of Material Culture in Leningrad (Saint Petersburg, Russia) (Galibin, 2001). The results were later published and extensively interpreted by A. S. Ostroverkhov (Ostroverkhov, 1993). The assemblage included vessels, bangles, beads, frits, slags, and the vitrified coatings of crucibles. Quantitative optical emission spectroscopy (QOES) was employed for the analyses. This extensive database provided the basis for several important conclusions about glass circulation in the North Pontic region. Yet it quickly became outdated with the advent of modern analytical techniques that are far faster and more precise. The question remains: can anything meaningful still be drawn from these early analyses?

In this study, we address this question by comparing the QOES results with modern data obtained by SEM-EDS on typologically similar samples— and, in a limited set of cases, on samples taken from the same objects.

#### Methods and Materials

QOES was performed on around 10 mg of archaeological glass placed into carbon electrode and burnt completely during 2-3 minutes of applied alternating current. The weighted oxides of Na, K, Ca, Mg, Mn, Al, Fe, Ti, Ni, Cu, Co, Ag, Pb and several other elements were reported, while SiO<sub>2</sub> was calculated as the difference between 100% and the sum of the measured oxides. The average relative error for each element was reported to be 10–15% (Galibin 2001).

The QOES was destructive and cannot be repeated on the same samples today. However, working with the material sampled by A. S. Ostroverkhov for V. Galibin in the Odesa Archaeological Museum, I was able to identify the original objects often with marks of sampling. I then sampled either comparable pieces, similar in date, type, and context, or, in some cases, the same objects themselves. The samples were analyzed using a Zeiss EVO 15 scanning electron microscope (SEM) equipped with an Ultim Max EDS detector (Oxford Instruments) at the Science and Technology in Archaeology and Culture Research Center (STARC), Cyprus Institute. Instrument calibration accuracy was verified using Corning A and B standard reference materials. The detection limit for most analyzed oxides was better than approximately 0.5

wt%. The analytical results exhibited an error margin below 10%, and in most cases below 5%.

The QOES results were reported as weighted oxides, which allowed direct comparison with the SEM-EDS results. The comparison was conducted following the approach described by (Rehren & Brügglér, 2020). For each weighted oxide, paired results were plotted on a biplot, linear regressions were calculated, and their distribution was evaluated relative to the bisector of the first quadrant, which theoretically represents perfect agreement between the two analytical methods.

#### Results

Based on this comparison, the weighted oxides can be divided into three groups.

The first group shows very good correspondence, with  $R^2$  values of 0.96–0.99 (MnO,  $Sb_2O_3$ , PbO, CuO). The second group exhibits overall correspondence but with a noticeable offset, with  $R^2$  values between 0.60 and 0.75 ( $Al_2O_3$ , FeO, MgO, CoO). The third group shows little to no correspondence, with K, Ca, and Na displaying very limited agreement between the two methods.

#### Discussion

The QOES analyses were checked against international reference glasses with known compositions (such as the Corning series) only sporadically. As a result, the older measurements are noticeably less accurate and show wider confidence intervals; the reported ranges for many oxides are broader than those obtained with modern analytical techniques.

QOES required burning relatively large portions of each sample, which tended to “average out” chemical differences within a single vessel or bead. In some cases, the published results refer to a different part of an object than the portion of interest. Moreover, potassium remains a clear problem. The Saint Petersburg laboratory had a detection limit of 2% for potassium, meaning that any lower values were not recorded at all—even though potassium content is essential for identifying the chemical type of the glass.

Despite these limitations, the QOES analyses also offer some important advantages. Most importantly, they provide rare compositional data on ancient

glass from southern Ukraine, notably for those weighted oxides, which showed a good correspondence in the comparative analysis.

A few other case studies have shown good agreement between the Saint Petersburg laboratory and laboratories in the UK and USA, although these comparisons mainly concern metal artefacts. The glass data appear reasonably reliable as well, as suggested by their correspondence with LA-ICP-MS results from typologically identical vessels and beads published recently from several contexts.

Nevertheless, a direct numerical comparison between the QOES results and modern chemical analyses is, as we demonstrated it, not feasible. The most productive approach is to identify general patterns in the older dataset and compare these with patterns derived from modern techniques. Discussing these QOES results, we should focus on broad trends rather than precise values.

The conducted analysis allows us to draw conclusions not to treat the QOES data as obligatorily “incorrect”, but a cross-laboratory comparison (not a complete collection, but at least a limited sample) seems necessary in every conclusion drawn from the inquiries of QOES facilities.

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## 430. Beyond the Instruments: AI-Driven Integration of Multisensor Data in Archaeometry

*Martina Naso (University La Sapienza of Roma)*

*Nevio Dubbini (University of Pisa)*

*Arthur Leck (Université Bordeaux Montaigne)*

*Rémy Chapoulie (Université Bordeaux Montaigne)*

*Gabriele Gattiglia (University of Pisa)*

*Claudia Sciuto (University of Pisa)*

### Introduction

The growing accessibility of portable and non-destructive analytical instruments has transformed the study of archaeological materials, generating increasingly large and heterogeneous datasets. In particular, the integration of hyperspectral imaging (HSI), portable X-ray fluorescence (pXRF), and Raman spectroscopy enables comprehensive physico-chemical characterisation of artefacts directly in museum and field contexts. However, the interoperability, reliability, and reproducibility of such multimodal data pose critical challenges, as differences in data structure, calibration protocols, and acquisition environments often limit direct comparability and hinder large-scale synthesis. The lack of standardised workflows for merging and interpreting spectral and compositional information further complicates the extraction of meaningful patterns from complex datasets. Within this framework, and in response to these analytical and computational limitations, one of the main objectives of the AUTOMATA project (AUTOMated enriched digitisation of Archaeological liThics and cerAmics, <https://automata-eccch.eu/>) is to develop an integrated, AI-assisted workflow to process, validate, and interpret non-destructive analytical data on ceramics. A core component of this workflow is the design of a dedicated database infrastructure for the long-term storage, interoperability, and reuse of multisensor data, fully compliant with FAIR principles, thereby supporting reproducibility and data sharing across

research institutions. This work therefore addresses the following questions: (1) how can multisensor datasets be efficiently harmonised for large-scale comparative studies? (2) to what extent can artificial intelligence (AI) automatically help identifying errors and data quality issues? and (3) how can automated reasoning support the selection of analytical strategies based on material characteristics?

### Methods and materials

The study assemblage comprises 3 ceramic collections, including approximately 300 fragments, selected for their chronological and technological diversity. The first assemblage (lot 1) derives from an archaeological deposit in ancient Rennes, containing both domestic and workshop debris, including locally produced jugs and sigillata ware. The second (lot 2) includes sigillata sherds from different production centres, all recovered from a single archaeological context. The third (lot 3) consists of Bronze Age pottery associated with both domestic use and salt production. These lots, chosen according to their conservation state, morphology, and analytical potential, form a heterogeneous test set that encompasses a wide range of materials and manufacturing techniques. This diversity provides an ideal framework for evaluating sensor complementarity, testing data integration strategies, and identifying the main analytical and computational challenges arising from multisensor workflows.

Each fragment is first subjected to a sequence of non-invasive measurements using hyperspectral imaging (HSI), portable X-ray fluorescence (pXRF), and Raman spectroscopy, each instrument operating independently under controlled conditions. Data acquisition is performed manually by operators, following standardised protocols for positioning, calibration and measurement parameters, ensuring consistency across instruments and sessions. This stage produces raw spectral and compositional datasets that capture complementary physical and chemical properties of each artefact. The collected data are subsequently imported into a dedicated software environment designed to integrate sensor outputs, extract diagnostic features, and align spectral information across different modalities.

The AI module, partially trained on collections of labelled spectral datasets, performs several operations at this stage. It first executes a noise detection routine that employs statistical indicators, such as variance, skewness and signal-to-noise ratios, together with an analysis of the intrinsic noise distribution within each sample. By comparing these parameters with reference distributions derived from curated training datasets, the AI system can accurately characterise both the noise affecting each spectrum. This process enables a context-aware evaluation of spectral quality, distinguishing between signals that can be effectively denoised and those too corrupted or inconsistent to be retained. Once signal validity has been established, the AI module autonomously selects the most appropriate post-processing strategy. When diagnostic or chemically significant spectral features are detected, the system initiates standard multivariate analyses such as principal component analysis (PCA), clustering, or other unsupervised modelling methods designed for pattern recognition. These analyses are performed selectively and conditionally, ensuring focus on spectra meeting defined quality and relevance thresholds. The AI module also generates a comprehensive set of key performance indicators that quantify the outcomes of each analytical phase, including metrics of signal integrity, denoising efficiency and clustering confidence.

## Results

Preliminary results demonstrate the feasibility of automated cross-sensor data integration and quality assessment. The combined use of HSI and pXRF has already highlighted significant correlations between surface reflectance and elemental composition, while Raman spectroscopy provides complementary molecular information. The AI system successfully classifies spectra according to their quality, identifying non-informative or noisy acquisitions and flagging them for operator review. Initial tests indicate a high level of accuracy (>95%) in distinguishing valid versus invalid spectra, enabling a substantial reduction in manual post-processing. These outcomes suggest that AI can play an active role in automating the analytical workflow, from data validation to the selection of advanced chemometric procedures. The project

is also developing a database designed for long-term storage and interoperability of multisensor data, compliant with FAIR principles, thus supporting reproducibility and data sharing across research institutions.

## Discussion

This study, within the broader framework of the AUTOMATA project, advances the ambition of establishing analytical archaeometry as a reproducible and scalable discipline, capable of being implemented reliably outside the traditional laboratory context. By integrating sensor data and AI-based quality control, this study proposes a methodological shift toward autonomous data management systems capable of contextual decision-making. This approach not only increases analytical efficiency, but also enhances transparency and traceability in heritage science workflows. In the long term, such integrated frameworks could support field-ready diagnostic systems, assist non-specialists in instrument use, and foster shared standards for chemical data validation in archaeology. Future developments within AUTOMATA will focus on extending the integration of sensor outputs to include 3D spatial data, enabling the creation of enhanced digital artefacts replicas that combine geometric, physical and chemical information into a single enriched representation. In parallel, specific attention will be given to the design of a human-in-the-loop architecture, allowing real-time human intervention in critical cases where automated reasoning remains uncertain. This interaction model will ensure that expert judgement remains embedded in the analytical loop, supporting adaptive decision-making and continuous system learning. Ultimately, the convergence of multimodal sensing, AI-driven analysis, and structured 3D data management will provide the foundation for a new generation of interoperable, intelligent, and ethically responsible archaeometric infrastructures.

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## S47: Artificial Intelligence, a Step into the Post-digital Era of Archaeology?

*Grégoire van Havre, Universidade Federal do Piauí*

*Kayeleigh Sharp, Northern Arizona University*

*Mathias Bellat, Eberhard Karls University of Tübingen*

**Location:** Hörsaal 03

**Session Format:** Other Format

In the post-digital era in which we now exist, technology has been embraced and normalised such that we are disrupted by its absence rather than its presence (see Huggett 2015). While the post-digital paradigm strongly rejects the narrative of one-way technological progress and recognizes both the advantages and disadvantages of new technologies as engines of innovation, we have not yet fully realised the range of implications integration of AI poses. With hybridised coexistence of analogue and digital, formerly disruptive techniques like GIS or 3D modeling and spatial analysis have become foundational in contemporary archaeological practice. It is within this intellectual environment that emerging AI techniques are being widely adopted. The critical question that emerges is whether such post-digital era technologies are being embraced without adequate consideration of the implications not only for preservation of archaeological sites but intangible cultural heritage as well. This question emerges with the current state of affairs emerging in AI today (Gattiglia 2025).

In May 2025, OpenAI launched a contest called “OpenAI to Z Challenge”, aimed at locating archaeological sites in the Amazon region using OpenAI o3/o4 mini and GPT-4.1 (<https://openai.com/openai-to-z-challenge/>). As it was probably the first time a large public contest was launched on such an archaeological question, it also carried a lot of Indiana Jones-like discourse (“You are the digital explorer”, “Discover secrets hidden under the canopy”) and a popular colonial mythology of Eldorado (the city of Z). Among the open

data indicated were “high-resolution satellite imagery, published lidar tiles, colonial diaries, indigenous oral maps, past documentaries, archaeological survey papers” calling, in effect, to a variety of possible AI applications in archaeology.

At nearly the same time, Bellat and Orellana-Figueroa et al. (2025) reviewed the trajectory of the use of AI in archaeology into six categories (classification of archaeological remains, predictive modelling, automatic structure detection, digital heritage, text analysis and taphonomic classification). In their conclusions, they insist on the necessity of common procedures and workflows, and on the limited availability of open data. As a result, they point out the exploratory dimension of most research. In parallel, Casillo et al. (2025), in their review of AI for cultural heritage practice, highlighted a lack of standardised datasets in their conclusion. Gattaglia (2025) assesses the importance of data availability and transparency, and draws ethical concerns over the invisible materiality of AI.

As computers become more capable of simulating human reasoning through the production of texts, images, and other digital content, it is worth asking about their impact on archaeology and on the production of knowledge about past societies. While the idea of a fully robotic excavation remains in the realm of science fiction, we can already glimpse the possibility of producing and publishing research entirely through large-scale language (LLM) and computer vision (CV) models. Some questions to consider include: Is it possible to identify such models if not clearly stated? What would the bias be? What does this mean for science? How might this influence understanding of the past and the construction of the present? Are there any foreseeable consequences? Is it possible to slow or even stop the damage? Who has access to current tools and who benefits from them? Such are the practical and ethical questions archaeology must address as soon as possible, and which form the basis of this session, as future archaeologists will graduate with an LLM right in their pockets and CV detection will be the norm.

## Session aim

This session aims to be a marketplace of ideas and suggestions, of collaborations and knowledge transfer. Specifically, it aims to explore questions about the analytical and ethical use of AI in archaeology, including, but not limited to, those mentioned above. We wish to gather people interested in using Artificial Intelligence on their data, but who don’t know how to do so, and people who know how to, but lack data. We call for those who would like to test their models on new and unexpected datasets. While case studies are recommended, we understand they may be incomplete. Some questions for consideration include: How does AI safeguard the respect and collaboration with Native and traditional people? How accurately does AI reproduce and represent the past? As in the case of *OpenAI to Z Challenge*, are certain aspects of colonial mythology already embedded in it? Do the results of the application of AI on archaeological data necessarily relate to past people? What are the possible implications in the present and in the future?

## Accessibility & Ethics

We encourage accessible presentation materials, plain-language summaries, and disclosures on data sensitivity, cultural considerations, and potential harms. Work with restricted data should outline mitigation strategies (e.g., redaction, differential access). Please state open vs closed-world assumptions and how constraints affect the inclusion/exclusion of sensitive entities.

## Special Interest Group

This session is organised by the CAA SIG on Machine Learning.

## References:

Bellat, M.; Orellana Figueroa, J. D.; Reeves, J. S.; Taghizadeh-Mehrjardi, R.; Tennie, C.; Scholten, T. 2025. Machine learning applications in archaeological practices: a review. arXiv. DOI: <https://doi.org/10.48550/arXiv.2501.03840>.

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**10:30 – 10:50** 40. Unveiling Drawing Patterns in Magdalenian Rock Art: Clustering and Unsupervised Machine Learning for the Analysis of animal Depictions  
*Natalia González Vázquez (Universidad Autónoma de Barcelona); Juan Antonio Barcelo (Universidad Autónoma de Barcelona); Diego Garate Maidagan (Universidad de Cantabria)*

**10:50 – 11:10** 87. NLP Insights from the OpenAI to Z Archaeology Challenge  
*Annie Lamar (University of California); Sarah McClure (University of California)*

**11:10 – 11:30** 189. From Post-Digital to Post-Algorithmic Archaeology: Reflexive Data-Making and the Ethics of Absence  
*Gabriele Gattiglia (University of Pisa)*

**11:30 – 11:50** 219. Mapping Hidden Heritage: Self-Supervised Learning on LiDAR-Derived DEMs for Detecting Dry-Stone Walls in the Budj Bim Cultural Landscape

*Zexian Huang\*; Brian Armstrong\*; Billy Bell (Gunditj Mirring Traditional Owners Aboriginal Corporation); Martin Tomko\**

*\* University of Melbourne*

**11:50 – 12:10** 233. AI, Brazilian archaeology and Global South, or the Colonial Computer  
*Grégoire van Havre (UFPI); Bruno Carvalho Pereira Campos (UFPI)*

**12:10 – 12:30** 270. What do we actually model when we model with neural networks in archaeology?  
*Jordy Orellana Figueroa (University of Tübingen)*

**12:30 – 13:30** Lunch break

**13:30 – 13:50** 417. Applying Convolutional Neural Networks to Archaeological Skeletal Analysis: Toward Open-Access Bioarchaeological Methods  
*Kate Collette (Northern Arizona University); Kayeleigh Sharp (Northern Arizona University); Manuel Antonio Roque Soplapu (Universidad Nacional Pedro Ruiz Gallo)*

**13:50 – 14:10** 421. A Survey on Attitudes towards Artificial Intelligence in Archaeology  
*Elisa Paperini (University of Pisa); Michel Mickael (Institute of genetics and animal biotechnology of the Polish Academy of Sciences)*

**14:10 – 14:30** 432. Insites - Cultural Significance Assessment as Human-AI Collaboration

*Yael Alef (Technion - Israel Institute of Technology);  
Yuval Shafir (EdTech Consultant)*

**14:30 – 14:50** 449. Same or different? Assessing variability in Howiesons Poort backed artifact morphology and composition across southern Africa  
*Boqiang Huang (University of Cologne)*

**14:50 – 15:00** Discussion

## 40. Unveiling Drawing Patterns in Magdalenian Rock Art: Clustering and Unsupervised Machine Learning for the Analysis of animal Depictions

*Natalia González Vázquez (Universidad Autónoma de Barcelona)*

*Juan Antonio Barcelo (Universidad Autónoma de Barcelona)*

*Diego Garate Maidagan (Universidad de Cantabria)*

Magdalenian rock art, renowned for its intricate depictions of bison, horses, and other Ice Age fauna, offers a unique window into the symbolic and cultural world of Upper Paleolithic societies (Bicho et al., 2007). Since the beginning of the studies of these manifestations, archaeologists have relied on classifications to organize and analyze them. However, the study of these prehistoric images presents significant challenges due to their complexity and the subjective nature of traditional archaeological interpretations. Over the last decades, new quantitative and computational techniques have been developed and have aided the study of rock art (Barnett et al., 2024; Jalandoni et al., 2022). This paper introduces an innovative computational framework for clustering, using artificial intelligence and unsupervised machine learning, with the goal of recognizing patterns and shared characteristics from Magdalenian rock art.

Our approach begins by transforming images into numerical arrays, capturing both global and local visual characteristics. To manage computational complexity and reduce dimensionality, we apply feature extraction techniques that preserve essential stylistic and morphological information, along with compression tools such as Principal Component Analysis (PCA), to further distill the most informative features from the resulting long vectors.

For clustering and pattern discovery, we utilize unsupervised methods instead of traditional supervised (label-based) learning because the labels may have arisen from pre-conceived conceptions. In contrast, unsupervised methods allow clusters to emerge directly from the data, generating groups based on the similarity and differences of the visual features identified among the rock art images (Bellat et al., 2025; Hörr et al., 2014). This approach enables the identification of recurrent motifs, stylistic groupings, and potential regional or temporal variations in the depiction of bison and horses.

For this unsupervised image clustering approach, we use high-dimensional feature vectors that capture meaningful visual characteristics. These vectors, called embeddings, could have around 240000 dimensions. These embeddings preserve semantic similarity—visually similar images produce nearby vectors in feature space, enabling algorithms like K-means, ACP or hierarchical clustering to group related images effectively. We plan to explore a variety of algorithms and methodologies to test, validate and refine cluster boundaries, including semi-supervised methods, transfer learning, traditional machine learning techniques, deep learning and convolutional neural networks. This iterative process will help to establish a robust framework for hypothesis testing and archaeological interpretation.

The results demonstrate that unsupervised machine learning can reveal previously unrecognized patterns and relationships within Magdalenian rock art, offering new perspectives on artistic conventions, cultural transmission,



and the cognitive landscape of prehistoric communities. This interdisciplinary study underscores the potential of advanced computational methods to enhance the analysis of complex visual datasets in archaeology, bridging the gap between quantitative analysis and qualitative interpretation.

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## 87. NLP Insights from the OpenAI to Z Archaeology Challenge

*Annie Lamar (University of California)*

*Sarah McClure (University of California)*

The 2025 “OpenAI to Z” challenge invited participants to use AI applications to identify archaeological ‘hotspots’ in the Amazon, yielding a public corpus of proposals that reveal emerging trends and tensions in the computational turn of cultural heritage science. This paper presents a meta-analysis of those submissions using natural language processing (NLP) methods to identify recurring themes, conceptual framings, and technical priorities across hundreds of entries. By examining linguistic patterns and clustering models, we trace how AI for “site detection,” “object recognition,” and “digital excavation” are framed as solutions to epistemic and logistical problems that have long shaped archaeological practice. Yet these same proposals expose deeper ethical and methodological concerns: the uncritical reuse of training data scraped from cultural heritage platforms, the replication of colonial logics in predictive modeling, and the gap between open innovation rhetoric and data governance reality. We argue that the dataset of open-access “OpenAI to Z” contest submissions offers a unique mirror for understanding how archaeologists, technologists, and the public imagine AI’s role in heritage work, and how these perspectives risk re-inscribing extractive relationships between data, land, and knowledge. By combining quantitative text analysis with critical data ethics, this study contributes to emerging conversations on the limits of “open” datasets and the need for culturally informed, consent-based frameworks for AI in archaeology.

## 189. From Post-Digital to Post-Algorithmic Archaeology: Reflexive Data-Making and the Ethics of Absence

Gabriele Gattiglia (University of Pisa)

### Introduction

Over the last decade, archaeology has progressively entered what may be defined as a post-digital condition: a phase in which once-disruptive technologies have become normalised within everyday practice. We now notice digital technology more through its absence than its presence. Yet this normalisation conceals a renewed form of disruption: the rapid diffusion of Artificial Intelligence in archaeology. AI is reshaping how archaeological knowledge is produced and, with it, the epistemic status of data. The question is no longer whether archaeology has become post-digital, but whether it can integrate algorithmic agency without surrendering interpretative responsibility. This paper proposes the concept of *post-algorithmic archaeology* as a continuation and a critique of the post-digital paradigm. Building on earlier reflections on hybrid and composite intentionality (Gattiglia 2022), and focusing in particular on contemporary AI systems based on data-driven machine learning models, it argues that algorithmic systems possess a form of technological intentionality that shapes archaeological interpretation. Algorithms do not merely process data; they participate in the hermeneutic act. A key distinction is therefore required: while the post-digital condition describes the normalisation and invisibility of digital tools, the post-algorithmic condition foregrounds the interpretative consequences of delegating classificatory, inferential, and generative operations to opaque, data-dependent models operating under conditions of epistemic uncertainty. A post-algorithmic perspective, therefore, calls for situated hermeneutics: an awareness that both human and algorithmic agencies are intertwined in the making of archaeological meaning. However, unlike the post-digital condition, emerging from an overabundance of digital instruments, the post-algorithmic arises from a paradox of scarcity. Archaeology does not inhabit a world of Big Data but one of missing data. Legacy archives remain incomplete, datasets fragmented, and even

the most sophisticated AI models often operate in a vacuum of information. Computational power now exceeds the quantity, quality, and accessibility of archaeological evidence. The post-algorithmic turn, then, is not born from data abundance but from absence: from the recognition that algorithms risk reinforcing the void rather than filling it. Reflexive data-making and capta

To navigate this condition, the paper introduces the notion of reflexive data-making, aligned with Drucker's (2011) distinction between *data* and *capta*: information taken rather than given. Reflexive data-making acknowledges that archaeological information is always co-created through situated practices of observation, selection, and mediation. It is the practical process that generates the *capta*: the interpretative substance of archaeological knowledge. Within a post-algorithmic framework, recognising this interpretative genesis becomes crucial, for algorithms too now participate in the production of *capta*. The archaeological record is no longer merely read by algorithms; it is, to an extent, written by them. This perspective transforms the ethical and epistemic problem of AI. Rather than asking whether This is evident, for example, in AI-driven artefact classification or automated feature detection, where training data derived from legacy archives embed prior interpretative choices and silently privilege specific formal, typological, or spatial regularities. This perspective reframes the ethical and epistemic problem of AI. Rather than asking whether AI can "tell stories", the question becomes how its outputs can be rendered accountable to the genealogies of their data, models, and assumptions, emphasising conditions of interpretation rather than the narrative form of results.

### Algorithmic normativity and archaeonormativity

Recent discussions by Perry et al. (2025) on archaeonormativity, i.e. the normalisation of disciplinary routines that suppress the affective, social, and political dimensions of archaeological work, provide a productive parallel. Archaeology's increasing reliance on algorithms generates what might be called algorithmic normativity: the progressive standardisation of epistemic

procedures through machine-readable schemas. For instance, recording practices and classification systems are increasingly shaped by the requirements of interoperability and automated processing, constraining how archaeological variability can be expressed. Both archaenormativity and algorithmic normativity risk reducing the interpretative complexity of archaeological practice. Yet both can be countered through reflexive approaches that restore visibility to the co-creation of data and the redistribution of agency among humans, materials, and technologies. A post-algorithmic archaeology must therefore operate not against technology but within its mediation, making its effects explicit through critical awareness.

The infrastructural threshold: a pre-ImageNet moment

Initiatives such as MAIA (Managing Artificial Intelligence in Archaeology), SEADDA (Saving European Archaeology from the Digital Dark Age) COST Actions, and the ECHOES (European Cloud for Heritage OpEn Science) project are addressing the chronic scarcity and fragmentation of archaeological datasets. These networks can be understood as pre-critical nodes within archaeology's infrastructural turn: efforts to build interoperable archives, shared vocabularies, and open infrastructures before a coherent epistemological reflection has occurred. Their ambition evokes, by analogy, the preconditions that led to the creation of ImageNet for computer vision in 2009: not as a model to be replicated, but as a critical point of comparison. Yet if ImageNet marked the turning point of AI, it also exposed the ethical and epistemic dangers of large-scale standardisation: opaque provenance, cultural bias, extractive labour, and the reduction of complexity to computable categories. Archaeology now faces a similar threshold. The post-algorithmic challenge is not to replicate ImageNet but to imagine what an Archaeological ImageNet could, or should, be. This thought experiment functions as a critical provocation rather than a technical proposal: what would it mean to assemble a vast, machine-readable dataset that is also reflexive, transparent, and ethically accountable? Could an archaeology conscious of its *capta*-making practices ever construct an infrastructure that preserves heterogeneity instead of erasing it?

## Discussion

This thought experiment, the Archaeological ImageNet, is not a technical proposal but a critical provocation. It asks archaeology to confront the infrastructural consequences of its own digital transformation before they become irreversible. Just as ImageNet made AI possible at the cost of opacity and bias, the coming consolidation of archaeological data infrastructures could shape how the past is algorithmically understood for decades to come. The post-algorithmic perspective demands that this process remain transparent, plural, and reflexive, foregrounding the situated nature of all archaeological knowledge production.

## Conclusion

Post-algorithmic archaeology is therefore not a celebration of automation but a critique of its preconditions. It recognises that the real challenge of AI in archaeology lies not in the sophistication of algorithms but in the vulnerability and politics of the data, or rather the *capta*, that feed them. In a world where computational power has outpaced information, the priority is building reflective, inclusive, and ethically grounded infrastructures for archaeological knowledge. Engaging with emerging AI ethics practices, such as dataset documentation, model auditing, and transparency protocols, becomes essential to ensure accountability (e.g. Floridi *et al.* 2018; Gebru *et al.* 2021) without surrendering interpretative responsibility. Only by acknowledging the absence, opacity, and situatedness of our data can archaeology engage with AI beyond enchantment, transforming the algorithms from oracles into interpretive partners.

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## 219. Mapping Hidden Heritage: Self-Supervised Learning on LiDAR-Derived DEMs for Detecting Dry-Stone Walls in the Budj Bim Cultural Landscape

*Zexian Huang (University of Melbourne)*

*Brian Armstrong (University of Melbourne)*

*Billy Bell (Gunditj Mirring Traditional Owners Aboriginal Corporation)*

*Martin Tomko (University of Melbourne)*

Dry-stone walls are enduring markers of human landscape modification. Built without mortar, they embody both technical ingenuity and cultural expression, serving as boundaries, enclosures, and social signifiers. In Australia, they are a significant part of the post-contact colonial heritage. Within the Budj Bim Cultural Landscape, a UNESCO World Heritage site located in South West Victoria, Australia, these dry stone walls are managed alongside Indigenous heritage by Gunditj Mirring Traditional Owners Aboriginal Corporation (GMTOAC). Many wall networks remain unmapped, concealed beneath dense vegetation and located in areas that are inaccessible to field survey. Reliable documentation is crucial for heritage and ecological management as well as for wildfire mitigation and controlled burn planning. Traditional mapping methods including manual survey, aerial photography, or visual interpretation are time-consuming and spatially limited. Recent advances in remote sensing and deep learning have opened new possibilities for automated detection, yet two key challenges persist: (1) occlusion of low-relief features by vegetation, and (2) scarcity of labeled data needed for supervised model training. To address these limitations, this study presents DINO-CV, a self-supervised cross-view pre-training framework that leverages high-resolution digital elevation model (DEM) derivatives from airborne LiDAR. By learning structural representations directly from topography rather than color imagery, the approach enables large-scale, label-efficient mapping of heritage stone-wall systems in visually complex and inaccessible landscapes.

## Introduction

The Budj Bim Cultural Landscape in Victoria, Australia, contains extensive networks of colonial-era dry-stone walls in close proximity to a range of Indigenous heritage sites (Jiménez de Madariaga, 2021). These walls, constructed over a century ago, remain poorly documented due to dense vegetation and terrain complexity. Accurate mapping is vital for protecting this fragile cultural landscape and guiding heritage conservation. While supervised deep learning has shown promise in automating archaeological feature mapping, its success depends on large labeled datasets that are costly to produce. Moreover, traditional optical imagery fails in heavily vegetated terrain. To overcome these constraints, our study explores self-supervised learning on airborne LiDAR-derived DEM derivatives to detect subtle geomorphic patterns of dry-stone walls.

## Methods and Materials

### - Study Area and Data

We focus on a 301 km<sup>2</sup> region of the Budj Bim Cultural Landscape. Two visualizations of landscape are derived from the LiDAR data, after removal of vegetation (Fig.1): 1. Multi-Directional Hillshade (MHS) enhances linear and relief features by simulating illumination from multiple angles; and 2. Visualization for Archaeological Topography (VAT) integrates slope, openness, and sky-view factor to highlight micro-topographic variations.

Two datasets were developed and applied: (1) BudjBimLandscape—an unlabeled dataset of 188,000 image tiles used for self-supervised pre-training; and (2) BudjBimArea—a manually annotated subset of 7,100 tiles (25 km<sup>2</sup>) used for supervised fine-tuning and evaluation with six-fold leave-one-area-out cross-validation.

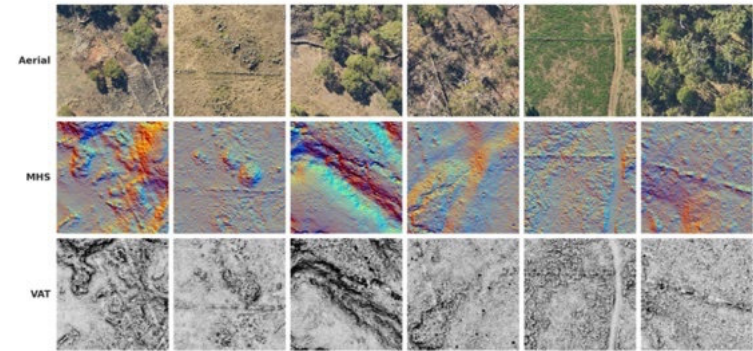


Figure 1: The aerial image (Row 1), Multi-directional Hillshade (MHS, Row 2), and Visualization for Archaeological Topography (VAT, Row 3) of dry-stone walls in the Budj Bim landscape. From left to right, columns show: (1–2) multiple parallel thin walls and an isolated thin wall; (3–4) thick, zigzag walls and a straight wall partially occluded by vegetation; (5–6) roadside straight walls with gate openings, and a heavily occluded wall segment.

### - Self-Supervised Cross-View Pre-training

DINO-CV (Fig. 2) extends the teacher–student knowledge-distillation framework of Caron et al. (2021) by introducing cross-view pre-training framework (Huang et al., 2025). A student network learns to align its feature representations with those of a teacher network trained on a fixed DEM view. During pre-training, the teacher observes a stable view (e.g., MHS) while the student alternates between MHS and VAT. This enforces the learning of view-invariant terrain representations, improving robustness to variations in data modality.

After cross-view pre-training, two independently trained encoders—one for MHS and one for VAT—are fused in a Pseudo-Siamese architecture for pixel-wise segmentation. Backbone architectures include ResNet-50, Wide ResNet-50-2, and ViT-Small/16, representing both Convolutional and Vision Transformer paradigms.

## Results

### - Mapping Accuracy

Across all architectures, DINO-CV outperformed both supervised ImageNet pre-training and self-supervised baselines, as shown in Table 1. On the annotated BudjBimArea dataset, it achieved an average of 81% F1-score and 68%



mean Intersection over Union (mIoU), surpassing supervised models by 3% to 4% points. The performance improvement demonstrates the value of domain-specific pre-training on DEM derivatives over generic image datasets.

- Label Efficiency and Spatial Generalization

When only 10% of training labels were used, DINO-CV retained over 90% of its full-data performance, confirming strong label efficiency, as shown in Table 2. Tested on an unseen area located 10 km from the training region (Fig.3), the model successfully delineated wall structures beneath dense vegetation, revealing previously undocumented alignments. These results demonstrate robust spatial transferability across varying vegetation and terrain conditions.

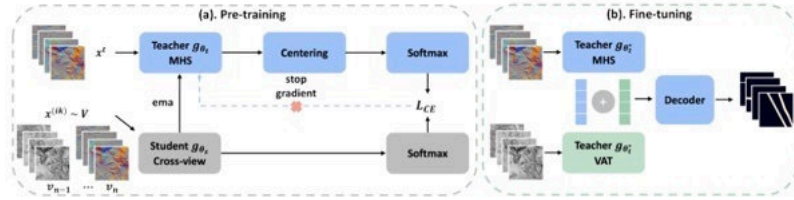


Figure 2: (a) The DINO-CV framework for self-supervised pre-training. At each training iteration  $k$ , the student network  $g_{\theta}$  receives a randomly sampled input from the collection of DEM-derived views (i.e., MHS and VAT), while the teacher network  $g_{\theta}$  receives a fixed view (MHS). (b) The Pseudo Siamese Network used for supervised fine-tuning. This architecture comprises two teacher networks, each pre-trained with DINO-CV on a distinct input view (MHS and VAT), enabling the extraction of complementary features for stone wall mapping.

Table 1: Stone wall mapping performances of ConvNet and ViT architectures. Evaluation metrics (i.e., Precision, Recall, F1 Score, and mIoU) are averaged over individual image tiles from the *BudjBimArea* dataset. The best performance for each backbone is highlighted in bold.

| Method                    | Backbone        | Param. | Pre-train Dataset | Pre.        | Rec.        | F1          | mIoU        |
|---------------------------|-----------------|--------|-------------------|-------------|-------------|-------------|-------------|
| Random Init.              | ResNet-50-Siam. | 46M    | -                 | 74.7        | 77.0        | 75.8        | 61.1        |
| Supervised                | ResNet-50-Siam. | 46M    | ImageNet-1K       | 76.9        | 81.4        | 79.1        | 65.4        |
| DINO (Caron et al., 2021) | ResNet-50-Siam. | 46M    | ImageNet-1K       | 75.7        | 74.3        | 75.0        | 60.0        |
| DINO-CV (ours)            | ResNet-50-Siam. | 46M    | BudjBimLand.      | <b>79.4</b> | <b>83.0</b> | <b>81.2</b> | <b>68.3</b> |
| Random Init.              | WRN-50-2-Siam.  | 138M   | -                 | 75.6        | 77.7        | 76.6        | 62.1        |
| Supervised                | WRN-50-2-Siam.  | 138M   | ImageNet-1K       | 76.4        | 82.5        | 79.3        | 65.7        |
| DINO-CV (ours)            | WRN-50-2-Siam.  | 138M   | BudjBimLand.      | <b>79.8</b> | <b>83.0</b> | <b>81.4</b> | <b>68.6</b> |
| Random Init.              | ViT-S/16-Siam.  | 42M    | -                 | 77.1        | 73.0        | 75.0        | 60.0        |
| Supervised                | ViT-S/16-Siam.  | 42M    | ImageNet-1K       | 74.2        | 82.4        | 78.1        | 64.0        |
| DINO (Caron et al., 2021) | ViT-S/16-Siam.  | 42M    | ImageNet-1K       | 76.8        | 81.1        | 78.9        | 65.2        |
| DINO-CV (ours)            | ViT-S/16-Siam.  | 42M    | BudjBimLand.      | <b>77.4</b> | <b>83.0</b> | <b>80.1</b> | <b>66.8</b> |

Table 2: Model mIoU (%) Performance on BudjBimArea training subsets.

| Method       | Backbone        | 50%         | 30%         | 10%         |
|--------------|-----------------|-------------|-------------|-------------|
| Random Init. | ResNet-50-Siam. | 51.6        | 38.3        | 21.4        |
| Supervised   | ResNet-50-Siam. | 64.9        | 62.9        | 49.3        |
| DINO-CV      | ResNet-50-Siam. | <b>67.7</b> | <b>67.2</b> | <b>63.6</b> |
| Random Init. | WRN-50-2-Siam.  | 53.6        | 38.4        | 22.5        |
| Supervised   | WRN-50-2-Siam.  | 65.3        | 63.6        | 49.7        |
| DINO-CV      | WRN-50-2-Siam.  | <b>68.0</b> | <b>66.7</b> | <b>63.8</b> |
| Random Init. | ViT-S/16-Siam.  | 52.9        | 42.8        | 14.3        |
| Supervised   | ViT-S/16-Siam.  | 63.2        | 61.6        | 56.4        |
| DINO-CV      | ViT-S/16-Siam.  | <b>65.1</b> | <b>63.2</b> | <b>58.9</b> |

## Discussion

The findings underscore the potential of self-supervised learning on topographic data for archaeological prospection. By exploiting elevation-based geomorphology rather than spectral information, DINO-CV mitigates vegetation occlusion and enables detection of low-lying heritage features invisible in aerial imagery. Its label efficiency and transferability make it suitable for large-scale heritage mapping where manual annotation is prohibitive.

Beyond technical performance, the approach offers wider cultural and practical benefits:

- Scalable documentation: Automated segmentation supports systematic inventory of heritage structures across vast landscapes.
- Non-invasive survey: DINO-CV enables reliable detection in remote or hazardous regions without physical fieldwork.
- Informed conservation: Mapped results can guide restoration planning, ecological management, and Indigenous-led heritage initiatives.

Although this work focuses on colonial dry-stone walls, the method is transferable to other archaeological features—including terraces, ditches, and earthworks—that share similar topographic signatures.

## Conclusion

We presented DINO-CV, a cross-view self-supervised learning framework that leverages LiDAR-derived DEM derivatives for automated mapping of dry-stone walls. Applied to the Budj Bim Cultural Landscape, DINO-CV achieved state-of-the-art accuracy and strong generalization under limited



supervision. The framework demonstrates how AI-driven analysis of LiDAR topography can advance digital documentation and preservation of hidden cultural heritage landscapes.

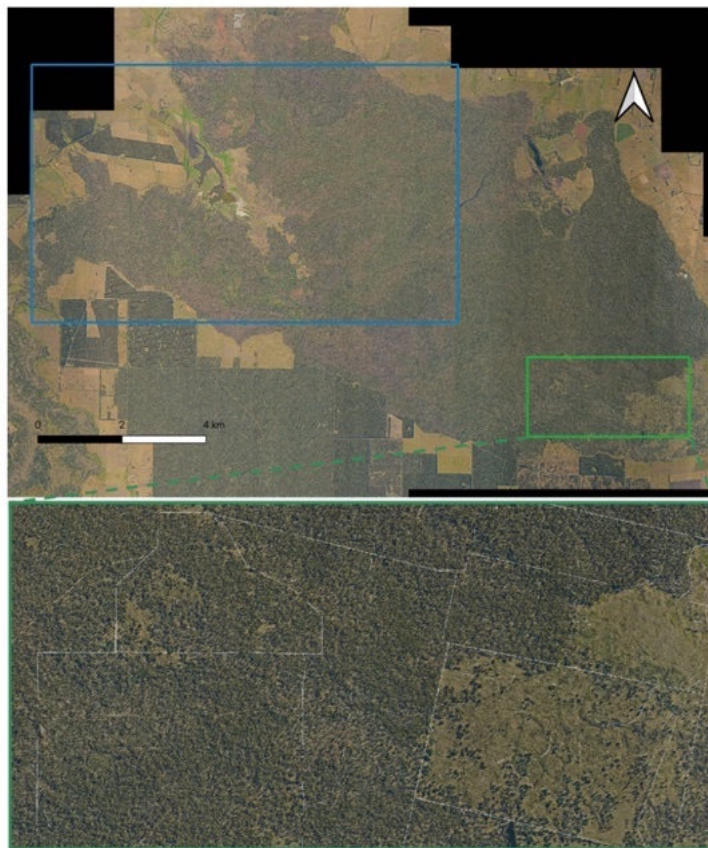


Figure 3: Generalization performance of the DINO-CV model with a ResNet-50-Siamese backbone on an unseen region within the Budj Bim Cultural Landscape. The upper panel shows the aerial imagery, with the blue rectangle marking the training area and the green rectangle denoting the unseen test area. The lower panel zooms into the unseen region, where the model accurately segments stone wall structures (annotated in white lines) beneath dense vegetation. These results highlight DINO-CV's ability to learn transferable geomorphic representations from multi-view DEM derivatives (MHS and VAT), enabling large-scale mapping beyond the spatial extent of the training data.

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## 233. AI, Brazilian archaeology and Global South, or the Colonial Computer

*Grégoire van Havre (UFPI); Bruno Carvalho Pereira Campos (UFPI)*

Brazilian archaeology offers an adequate scenery to study how Large Language Models (LLM) behave when confronted with data more distant from mainstream archaeological literature and training sources. This communication critically explores such a problem by systematically testing how models answer to question about archaeological contexts from the Global South. We follow Gattiglia (2025) in that an application of AI requires a critical perspective due to risks of distortion and inadequate interpretation.

Our methodology involves designing simple and direct questions that must contemplate all three variables of time, space and culture, always related to Brazilian archaeology. We also apply these questions in three different environments: offline, online, and online with additional articles. The first results show a high level of incoherent and made-up information it the two first

environments, only mitigated when new texts are given. These hallucinations in LLMs can be explained through internal mechanisms, as recently detailed by Kalai et al (2025), but they could also indicate a limitation in dealing with Global South Indigenous chronologies, places and cultural behaviours, as well as modern research produced, in Portuguese, by Brazilian archaeology. It then becomes worrisome, considering its growing use in education, that AI might be producing answers on Global South contexts from a Global North perspective.

This research represents an important step in developing responsible practices in the use of AI in archaeology, emphasizing the necessity of a thorough examination when dealing with under represented archaeological contexts. By pointing out the limitations of such a tool, we hope to foster more equal and culturally sensitive perspective when integrating AI in archaeology.

## 270. What do we actually model when we model with neural networks in archaeology?

*Jordy Orellana Figueroa (University of Tübingen)*

Recent (and not-so-recent) advances in the performance of neural networks have been reflected in their increasingly widespread use in archaeological research, overtaking other machine learning methods adopted earlier (e.g. random forests), sometimes by a large margin (Bellat et al. forthcoming; Eleftheriadou et al. 2025). However, as is the case with new technologies and new methods, an incentive to adopt (and publish) as early as possible can arise, even when a thorough understanding of the applied methods may be incomplete, leading this to sub-optimal applications. This is especially true as neural networks are almost always ‘black box’ models, whose reasoning cannot be easily scrutinised, if at all. While methodological issues have already been highlighted for some specific case studies (Bellat et al. forthcoming; Courtenay et al. 2024), the discussion has been focused on the specific

details of the particular implementation and data used, if not also restricted to a specific type of input data altogether.

This contribution seeks to approach the problem from a higher level of abstraction; looking not only at specific case studies, the specific data used, and the specific methodology, but also the more (both computational and archaeological) theoretical underpinnings of the choice of data and methods applied. The goal is to go beyond a critique of the classification labels used to train the model, but rather examine what we are truly training our algorithm to model with these labels, what are the limits of the conclusions that could be drawn from the model’s results, and how to align the methodology to properly address the research goals (and spot when it cannot). We will look at these problems through the lens of specific case studies serving to discuss best practices to improve their theoretical and methodological strengths.

Exhaustively examining the subject of aligning the applications of neural network to serve archaeological questions could arguably be a field of its own, especially as these issues are not exclusive to neural networks, machine learning, or statistical (if not also scientific) methods, nor even limited only to archaeology. Thus, for expediency we will restrict the scope of the discussion to focus foremost on the aspects that are more likely to be encountered with archaeological research and data. These aspects include small datasets, class imbalances in classification, and the encoding of data (viz. artefacts, assemblages, sites) into inputs, as well as how these factors affect and are affected by the choice of methodology writ large.

The knowledge and understanding of how neural networks work and how they can be best applied to archaeological research has very likely matured since its beginnings in the previous decade (Bellat et al. forthcoming; not to mention machine learning in general), as can be seen with the Managing Artificial Intelligence in Archaeology (MAIA) COST action and the CAA’s own Machine Learning & Artificial Intelligence in Archaeology Special Interest Group. Despite these very welcome advances, researchers unfamiliar with the application of neural networks to archaeological research would be greatly assisted by an exploration such as that presented here. The hope is

that by presenting precise and specific points of conflict between how archaeologists apply neural networks and what they wish to and can uncover with them, scholars are better able to navigate these possible pitfalls, develop methodologies that more closely align with their actual research goals, understand the strength and weaknesses of their data and neural networks, and better temper their conclusions to the strength, validity, and rigour of their methods.

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## 417. Applying Convolutional Neural Networks to Archaeological Skeletal Analysis: Toward Open-Access Bioarchaeological Methods

*Kate Collette (Northern Arizona University)*

*Kayeleigh Sharp (Northern Arizona University)*

*Manuel Antonio Roque Soplapuco (Universidad Nacional Pedro Ruiz Gallo)*

Traditional methods of biological profile estimation from skeletal remains are labor-intensive, expertise-dependent, and often inaccessible to researchers in regions lacking formal bioarchaeological training infrastructure. In Northern Peru, where this research was conducted, archaeology students face significant barriers to specialized osteological education. Formal courses in bioarchaeology are scarce or nonexistent at many institutions, and when available, they remain prohibitively expensive for many students. While Bayesian methods like Transition Analysis have demonstrated measurable improvements in tasks like age estimation - particularly among older individuals - manual classification remains dependent on specialized training and hands-on experience, introducing observer error and limiting reproducibility across different analysts (Boldsen et al. 2002). This project attempts to address some of these challenges by developing a deep learning method for age and sex estimation from skeletal remains, with a commitment to open-access principles that democratize osteological knowledge and ensure bioarchaeology is accessible to local researchers and students.

Recent studies of deep learning approaches in osteology have demonstrated remarkable potential for skeletal analysis, achieving classification accuracy well above 90% for age and sex estimation from diagnostic medical images (Faisal and Rogers 2025; Liu et al. 2021; Prokop-Piotrkowska et al. 2021). Building on these advances, this project applies convolutional neural networks (CNNs) to skeletal remains from archaeological contexts, specifically targeting regions of established morphological significance for age and sex estimation.

The dataset comprises images from 180 individuals from eight sites in Northern coastal Peru, each labeled into binary categories based on prior osteological analysis: young (<45 years) and mature (≥45 years) for age estimation, and male and female for sex estimation. The reduction to binary classification for age mitigates challenges inherent to the limited dataset size. The collection exhibits significant taphonomic variation between burials, a reality that frequently defines bioarchaeological collections. The vast majority of successful deep learning applications in osteological analysis to date have focused on carefully curated medical collections, making projects like this one which confront the preservation challenges of archaeological contexts critically important for advancing the field.

Two separate CNN models are currently in development for age and sex estimation. To address the fundamental limitation of dataset size, the project employs transfer learning and data augmentation strategies. Models are pre-trained using the ImageNet dataset, a large-scale image collection, allowing the networks to leverage previously learned feature extraction capabilities and apply them to the smaller training dataset. Data augmentation artificially expands the available training examples through random rotation, scaling, cropping, and mirroring, improving model generalization and reducing overfitting risk.

A critical component of this research is model interpretability. Saliency mapping techniques, particularly Gradient-weighted Class Activation Mapping (Grad-CAM), will be employed to visualize which skeletal regions most strongly influence classification decisions. This approach provides insight into both documented diagnostic features and potentially novel morphological indicators, creating opportunities for osteological discovery rather than simply automating existing methods. Such visualization techniques also enable critical evaluation of whether the models are learning anatomically meaningful patterns or spurious correlations.

The project employs performance metrics specifically suited to binary classification tasks. Matthew's Correlation Coefficient serves as the primary evaluation metric, providing a balanced measure that accounts for all confusion matrix categories, offering an honest performance assessment that weighs

all incorrect classifications as equally problematic. Potential algorithmic biases arising from uneven sample representation and taphonomic variability are actively addressed through critical interpretation of model performance across classes and systematic evaluation of how bone completeness affects classification accuracy. This reflexive approach prioritizes transparency and ensures that resulting models do not propagate bias or obscure research limitations.

Community engagement stands central to this project's mission. Museum collaborators in Peru have expressed strong interest in both research outcomes and potential applications for their collections. Model code, documentation, and annotated datasets will be shared via cloud repositories to support replication, education, and future collaboration with these stakeholders. Any future work with these data will be approved by museum collaborators. This open-access approach democratizes AI methods, challenges traditional paradigms of privileged knowledge in bioarchaeology, and ensures partner institutions retain full control over trained models and derived data.

This work contributes to a growing body of research exploring artificial intelligence applications in osteological analysis. The implications extend beyond academic bioarchaeology to support field-based identification efforts, including forensic applications where rapid, image-based age and sex estimation could assist in victim identification and humanitarian response. Such interdisciplinary and accessible tools can transform how skeletal data are interpreted and mobilized in both research and applied contexts. This research demonstrates deep learning's potential to augment rather than replace traditional methods, providing computational tools that complement osteological expertise. By presenting initial results at this session, we aim to encourage fellow researchers working with comparable collections to contribute their data and methodologies, fostering a collaborative approach that allows the project to progress beyond constraints of a single limited dataset or geographic region.

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## 421. A Survey on Attitudes towards Artificial Intelligence in Archaeology

*Elisa Paperini (University of Pisa)*

*Michel Mickael (Institute of genetics and animal biotechnology of the Polish Academy of Sciences)*

### Context

Artificial Intelligence (AI) is increasingly shaping how archaeological knowledge is produced, analysed, and communicated. From pattern recognition in remote sensing to predictive modelling and automated

classification of artefacts, AI-driven approaches are transforming archaeological research's epistemic and practical dimensions. However, while technical innovation has advanced rapidly and discussions around AI in archaeology are increasingly widespread, the extent of sustained methodological and theoretical reflection on how archaeologists and related professionals perceive, adopt, and critically engage with AI appears to vary. In other words, while awareness is growing, the depth and integration of theoretical and methodological considerations of AI use in archaeology may still be emerging.

This consideration led to the creation of a collaborative survey within MAIA COST Action (CA23141) – Managing Artificial Intelligence in Archaeology. The group, composed of researchers from diverse disciplinary and national backgrounds, identified a shared need to investigate how AI is understood and experienced across archaeological domains. The survey originated from a collective brainstorming session held during the MAIA kick-off meeting in Seville in May 2025, where participants highlighted the necessity of grounding theoretical discussions on empirical evidence about current practices and perceptions.

The project seeks to explore the sociotechnical landscape of AI in archaeology — how expectations, ethical concerns, and professional roles interact to influence how archaeologists apply AI methods in practice and how these applications, in turn, shape theoretical perspectives.

### Main Argument

The paper presents the methodological framework of the MAIA survey. Its construction involved an interdisciplinary process that brought together archaeologists, data scientists, ethicists, and heritage professionals. The underlying premise is that AI adoption in archaeology is not merely a technical matter but a theory-laden practice — reflecting implicit assumptions about knowledge, agency, and interpretation.

The methodological contribution of this study lies in three main aspects:

#### 1. Collaborative and Reflexive Design

The survey was co-created through an open, iterative process within MAIA WG1. It began with a collective brainstorming phase in which several key themes emerged—such as ethics, the meaning of 'state of the art', the intended audience, and technical issues. These topics were subsequently refined through further discussion and transformed into structured questions. The collaborative approach ensured inclusiveness across subfields and professional contexts, allowing the questionnaire to develop as a shared methodological object that integrated expertise from the humanities and computational sciences.

## 2. Mixed-Methods Structure

The instrument combines quantitative and qualitative components to capture the complexity of attitudes towards AI. Closed-ended questions address frequency of use, perceived benefits, barriers, and ethical concerns, enabling statistical comparison across occupational categories and geographic regions. Open-ended questions invite participants to articulate personal reflections and disciplinary critiques, providing material for qualitative thematic analysis. This dual structure acknowledges that perceptions of AI involve narratives and disciplinary imaginaries.

## 3. Theoretical Framing and Analytical Potential

Conceptually, the survey builds on theories of how technology shapes research practices and how researchers reflect on their methods within digital archaeology. Technologies are not neutral tools; we use them to create models that reflect biases introduced by how they are perceived, designed, and used. Perceptions and expectations of AI vary depending on professional role, institutional setting, and technical literacy, revealing an uneven landscape of adoption and understanding.

The current contribution focuses on the methodological architecture, including questionnaire structure, recruitment strategies, and ethical protocols. Data collection relies on voluntary, anonymous participation through a web-based form distributed across professional networks, academic mailing lists, and MAIA communication channels. Ethical approval was secured, and informed consent was obtained before participation, ensuring transparency and data protection in compliance with European research standards.

## Applications or Implications

This methodological study has multiple implications for the theory and practice of digital archaeology.

First, it provides a model for interdisciplinary methodological collaboration. The collaboration enables people with different expertise to come together, exchange ideas and working practices, and pursue common goals.

Second, the survey constitutes a scalable empirical foundation for future comparative analyses. Generating a cross-sectional dataset covering different professional profiles enables systematic mapping of AI adoption patterns across Europe and beyond. Such data can inform the development of best practices, training curricula, and policy recommendations for responsible and sustainable AI use in heritage and archaeology.

Third, the project fosters a critical dialogue between technical capability and disciplinary identity. Understanding how practitioners conceptualise AI (whether as a neutral instrument or a partner in interpretation) can help re-frame ongoing debates about agency, interpretation, and automation in archaeological reasoning.

Finally, this initiative reflects MAIA's broader mission: to advance understanding of how AI can be responsibly and effectively integrated into archaeology. As a COST Action, MAIA fosters collaboration among archaeologists and computer scientists to establish shared ethical and methodological standards for AI use in archaeology. The survey supports MAIA's goal of promoting interdisciplinary dialogue and providing the foundations for more cohesive and reflective European archaeological research.

In conclusion, this survey shows how collaborative and reflective work can support methodological progress in digital archaeology. It contributes to ongoing discussions about how archaeologists use and think about AI in their research. The experience of designing and implementing the survey has helped clarify shared challenges and opportunities, showing that methodological reflection can emerge naturally through practical collaboration and open exchange.



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## 432. Insites - Cultural Significance Assessment as Human–AI Collaboration

*Yael Alef (Technion - Israel Institute of Technology)*

*Yuval Shafirri (EdTech Consultant)*

InSites is an experimental Gen-AI assistant designed to operationalize Context-Based Significance Assessment for cultural heritage. Developed in response to accelerating societal and technological change, it addresses three interrelated challenges: the complexity of cultural reasoning; the need for inclusive representation of community and societal values; and ethical risks to professional authority, accountability, and bias arising from Gen-AI’s disruptive potential. Rather than porting procedures, InSites explores new Gen-AI affordances by restructuring assessment as a transparent, evidence-grounded, human-in-the-loop workflow. It embeds domain knowledge, applies guardrails for traceability, and enforces structured reasoning through a modular process. Preliminary observations from pilot deployments indicate

that Gen-AI could act as a cognitive partner, with early signs of improved articulation of values and support for multivocal analysis. This paper focuses on the system’s conceptual design and guiding principles, rests on the premise that Gen-AI should augment, not replace, human judgment.

## 449. Same or different? Assessing variability in Howiesons Poort backed artifact morphology and composition across southern Africa

*Boqiang Huang (University of Cologne)*

### Introduction:

Backed artefacts of the southern African Middle Stone Age are among the most widely discussed examples of standardized technology linked to the Howiesons Poort (HP), which dates to around 65–60 thousand years ago (ka). Recent work by Way et al. [1] argues that the morphological similarity of these artefacts across geographically distant sites reflects enhanced social connectivity and information transmission during the Final Pleistocene. This conclusion is based primarily on a geometric morphometric analysis of 459 landmarked artefacts from 7 South African sites, as well as 95 artefacts from a late-Holocene outgroup assemblage in Lake George, Australia. While the authors employed Principal Component Analysis (PCA) for dimensionality reduction and Linear Discriminant Analysis (LDA) with Leave-One-Out Cross-Validation (LOOCV) for classification, we posit that modern machine-learning methods could enhance classification accuracy and expose overlooked structure in the dataset. Thus, our research investigates whether advanced neural-network-based classification, coupled with archaeological feature extraction, can provide deeper insights into technological standardisation and inter-site relationships among Howiesons Poort backed artefacts.

### Methods and Materials:

We used the openly shared dataset provided in [1], consisting of 459 two-dimensional landmark configurations of backed artefacts from 7 South

African sites (Diepkloof - 21, Howiesons Poort - 42, Klasies River - 93, Klipdrift Shelter - 21, Pinnacle Point - 21, Rose Cottage - 132, Sibudu - 129) and 95 landmarked artefacts from Lake George, Australia. To maintain continuity with the original methodology, we applied the same Generalised Procrustes Analysis (GPA) for shape alignment and scaling. GPA also enabled us to demonstrate that the traditional HP analytical approach of fixing artifact ends along a primary morphological axis is mathematically equivalent to GPA, validating our methodological comparability to prior work.

We diverged from prior methodology in two ways. First, rather than relying exclusively on PCA landmark reduction, we incorporated empirical geometric feature extraction using PyREnArA (Python-R-Environment for Artifact Analysis), a toolbox that calculates archaeologically meaningful morphometric variables [2-3]. Second, instead of classical LDA, we implemented a fully connected neural network classifier, trained using 80/20 training-test splits with systematic LOOCV to ensure direct comparability to the results in [1].

Results:

(1) Neural network classification substantially outperformed LDA. The performance of LDA degraded notably when PCA was used to reduce dimensionality. By contrast, neural networks trained on either PCA-derived or empirical PyREnArA features achieved higher accuracy. This shows that the geometric relationships in Howiesons Poort backed artefacts are too complex to be captured by linear discriminant space.

(2) New insights into variation in the Pinnacle Point. Previous interpretations treated Pinnacle Point backed artefacts as technologically distinct. However, our feature-level analysis shows that most of the observed differences are not due to artefact morphology, but rather to the divergent landmarking strategy employed during digitisation. The sampling method altered landmark distributions in a way that was different from other sites, creating an artificial morphological distance in PCA space. Therefore, Pinnacle Point should not be considered a technological outlier, but rather the result of inconsistent data acquisition.

(3) Outgroup comparison supports both regional uniqueness and associative links. Australian artefacts from Lake George exhibit a distinct morphometric

identity compared to HP assemblages. However, classification confusion matrices suggest a weak yet consistent resemblance to the Sibudu assemblage. This suggests convergent functional morphology rather than diffusion, offering nuance to the interpretation that southern African backed artefacts occupy a constrained shape-space.

Discussion:

Our results confirm that Howiesons Poort artefacts are morphometrically standardised, but also reveal two insights that are inaccessible through traditional linear modelling. Firstly, modern machine learning reveals a hierarchical structure among HP sites, suggesting technological evolution within a shared behavioural network. Secondly, data inconsistencies, particularly with regard to landmarking choices, can artificially generate archaeological hypotheses of "technological distinctiveness". Therefore, neural-network classification provides increased analytical accuracy and improved diagnostic sensitivity to methodological artefacts. Furthermore, the clustering of southern African sites reinforces the significance of inter-group technological learning. This aligns with the argument that long-distance social networks played an adaptive role in the resilience of the late Pleistocene population.

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## S49: Bridging Micro and Macro Perspectives in the Modelling of Past Human Ecosystems

*Eleftheria Paliou*, University of Cologne

*Andreas Angourakis*, Ruhr University Bochum; University of Cologne

**Location:** Franz König Saal

**Session Format:** Standard

Ongoing and current discourse in socio-ecological research has highlighted the need to explore the types and intensity of human–environment interactions across a variety of temporal and spatial scales (Roberts et al. 2024; Kintigh et al. 2014). Computational archaeology is integral to such investigations, since it enables the study of the dynamic interplay between human behaviour and environmental change, including shifts in climate, vegetation cover, and faunal and floral populations, through a deep-time and multi-scalar perspective. At the macro scale, advances in computational modelling and the growing availability of large datasets on past settlement distributions, radiocarbon dates, and climatic variables have highlighted broader trends and aggregate patterns in the archaeological record, suggesting reciprocal influences between altering socio-economic and environmental conditions. Nonetheless, a deeper understanding of the local processes that give rise to macro-patterns is notoriously challenging to achieve. This difficulty stems from several factors: the uneven availability and quality of archaeological and environmental data across regions, the problem of equifinality (i.e. distinct pathways can produce similar large-scale outcomes), and the tendency of macro-scale analyses to smooth over local dynamics and short-term fluctuations, thereby obscuring the causal mechanisms that operate at finer scales. On the other hand, microscale studies have offered essential insights into the dynamic relationship between human societies and ecological change at the local level. Especially notable is the contribution of ethnoarchaeological approaches that look into the ecological perspectives of

Indigenous and local communities (Sherjon et al. 2015; Whitaker et al. 2023; Pisor and Jones 2021; Welch-Devine et al. 2020), and multidisciplinary research that brings together high-resolution data from material, archaeobotanical, zooarchaeological and paleoenvironmental studies. However, the value of local level understandings for socio-ecological research is increasingly scrutinised due to concerns regarding their direct applicability across diverse contexts and the difficulty of making valid cultural parallels. In this respect, computational approaches, such as Agent-Based Modelling (ABM), that gain insights from ethnoarchaeological and small-scale studies offer significant methodological advantages, as they focus on exploring microscale processes, rather than relying on direct cultural analogies, allow rigorous hypothesis testing, and have the potential to highlight non-linear feedback between local and global processes.

This session aims to bring together micro and macro perspectives on the modelling of past human ecosystems, seeking a more comprehensive understanding of the interdependence between microdynamics and macro patterns. It invites contributions discussing cross-scale approaches to computational modelling and theoretical frameworks that seek to make explicit the links between local-level human action and global environmental impacts. Furthermore, we are particularly interested in approaches to computational modelling that gain insights from Indigenous and traditional ecological knowledge. We also encourage contributions that explore the socio-ecological dynamics of resource use, depletion, and renewal, as well as interdisciplinary eco-archaeological approaches that bring together ethnoarchaeology, archaeological science methods, and computational modelling. More broadly, we invite works on computational modelling (e.g., simulations, GIS-based models, equation-based models, agent-based models, etc.) which look into:

- The response of hunter-gatherer, agropastoralist and urban populations to ecological change
- anthropogenic impacts on the environment in the long- and short-term, at smaller and larger spatial scales
- ecological sustainability and resilience in the past and present

- technological advances in computational modelling of socio-ecological systems

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|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>10:30 – 10:50</b> | <p>252. Generative Inference and Reflexive Modelling: Bridging Scales in Socio-Ecological Archaeology<br/> <i>Martin Hinz (Institute of Archaeological Sciences, University of Bern); Sophie C. Schmidt (Institute for Pre- and Protohistoric Archaeology, Kiel University)</i></p>                                                                                                                                                | <b>11:50 – 12:10</b> | <p>418. Modelling and simulation of mixed production and community energy balance in the Neolithic: the Cueva de la Dehesilla case study<br/> <i>Juan Antonio Fernandez Morales (Universidad de Sevilla); Jesús María Barandica Fernández (Universidad Complutense de Madrid); Daniel García Rivero (Universidad de Sevilla)</i></p> |
| <b>10:50 – 11:10</b> | <p>118. Paleoenvironmental reconstructions of the Early and early Middle Pleistocene as a scene for “Out of Africa” dispersals<br/> <i>Kamilla Lomborg*; Nicolas Viovy (Laboratoire des Sciences du Climat et de l'Environnement); Carolina Cucart-Mora*; Jan-Olaf Reschke*; Christine Hertler (Senckenberg Research Institute); Marie-Hélène Moncel*</i></p> <p><i>* CNRS UMR 7194 HNHP Institut de Paleontologie Humaine</i></p> | <b>12:10 – 12:30</b> | <p>*cancelled*<br/> 403. Modelling travellers in Indian proto-history<br/> <i>Salil Sayed (Deccan College PGRI); Prabodh Shirvalkar (Deccan College PGRI)</i></p>                                                                                                                                                                    |
| <b>11:10 – 11:30</b> | <p>105. Trading Mediterranean summers for northern winters - studying hominin subsistence behaviour during the first occupation of northwestern Europe<br/> <i>Jan-Olaf Reschke*; Carolina Cucart-Mora*; Kamilla Lomborg*; Matt Grove (University of Liverpool); Christine Hertler (ROCEEH); Marie-Hélène Moncel*</i></p> <p><i>*CNRS</i></p>                                                                                      | <b>12:30 – 13:30</b> | Lunch break                                                                                                                                                                                                                                                                                                                          |
| <b>11:30 – 11:50</b> | <p>236. The ecological impact of early fishing: between ceramic hunter-gatherers and early farmers in the Southern Buh river valley (Southern Ukraine)<br/> <i>Dmytro Kiosak (Leibniz Zentrum für Archäologie)</i></p>                                                                                                                                                                                                             | <b>13:30 – 13:50</b> | <p>12. From Macro Patterns to Micro Processes: Integrating Regional Spatial Analysis and Intra-Site Investigation to Reveal Temporal Cycling in Iron Age IIA Negev Highlands<br/> <i>Itay Lubel (Hebrew University of Jerusalem)</i></p>                                                                                             |
|                      |                                                                                                                                                                                                                                                                                                                                                                                                                                    | <b>13:50 – 14:10</b> | <p>234. Bottom-up or top-down? Modelling natural administrative divisions in Final Iron Age (11th-13th century) Estonia<br/> <i>Kristo Siig (Tallinn University); Kaarel Sikk (Tartu University)</i></p>                                                                                                                             |
|                      |                                                                                                                                                                                                                                                                                                                                                                                                                                    | <b>14:10 – 14:30</b> | <p>122. Clean Romans, Dirty Air, and Trimmed Forests: The environmental impact of Ancient Baths<br/> <i>Marta Galindo Diaz*; Jeroen Poblome*; Bart Muys*; Dirk Saelens*</i></p> <p><i>* KU Leuven</i></p>                                                                                                                            |

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|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:30 –<br/>14:50</b> | 89. Climate, Crisis, and Settlement Dynamics: A Quantitative Model of the Roman-Early Medieval Transition in the Moselle Valley<br><i>Ilenia Petrarulo (University of Luxembourg); Giacomo Fontana (Texas Tech University)</i> |
| <b>14:50 –<br/>15:10</b> | Discussion                                                                                                                                                                                                                     |

## 12. From Macro Patterns to Micro Processes: Integrating Regional Spatial Analysis and Intra-Site Investigation to Reveal Temporal Cycling in Iron Age IIA Negev Highlands

*Itay Lubel (Hebrew University of Jerusalem)*

### Introduction

Understanding human-environment interactions in marginal landscapes presents a fundamental methodological challenge: macro-scale analyses reveal aggregate site patterns and broader socio-ecological trends but obscure the local microdynamics that generate them, while microscale investigations illuminate specific adaptive practices but cannot explain regional spatial organization. Bridging these perspectives is essential for understanding the interdependence between local-level human action and landscape-scale patterns, particularly in environments where mobile populations respond to ecological constraints through temporal rather than purely spatial strategies. The Iron Age IIA (c. 980-830 BCE) Negev Highlands provide an ideal test case for multi-scalar spatial analysis. This arid desert-steppe region, less favourable than the Mediterranean zone but more favourable than other desert regions, witnessed the appearance of 510 stone-built sites associated with agropastoral populations exhibiting material culture combining autochthonous desert traditions with Mediterranean Levantine influences, in parallel to intensive copper production in the nearby Arabah valley (Ben-Yosef 2023).

Despite inherent environmental challenges, the archaeological record displays clear site clustering, with densities reaching 4.2 sites per km<sup>2</sup>. This spatial configuration presents a puzzle: how did mobile populations organize their landscape use to sustain such concentrated occupation in this harsh environment during economic intensification?

This study integrates regional spatial analysis of all 510 sites with detailed intra-site survey at five locations to investigate how spatial organization at both macro and micro scales reveals the adaptive strategies structuring human-environment dynamics in this agropastoral system.

### Methods and Materials

Regional spatial analysis employed GIS-based modelling incorporating all 510 Iron Age IIA sites with environmental variables including topography, arable land, permanent water sources, and movement corridors. Multi-scalar point pattern analysis (Bevan 2020) examined clustering patterns across distances from 500m to 15km, with statistical significance established through Monte Carlo simulations. Bivariate analysis differentiated enclosed compounds, perceived by many as central sites, from other site types to identify hierarchical spatial organization. Proximity analysis measured cost-distance walking times to key environmental resources using Tobler's hiking equation, revealing systematic resource preferences across the system.

Intra-site survey targeted five sites representing diverse architectural types and environmental contexts from previously under-investigated areas. Systematic surface documentation of pottery scatters and architectural features within 250m-in-diameter cells examined: (1) spatial distribution of built features relative to environmental conditions (aspect, streambeds, topography); (2) relationships between mobile and immobile finds. The survey clearly established cases of disconnection between architectural and mobile remains, indicating further (possibly ephemeral) activity beyond stone-built structures. Analysis of the survey results specifically examined spatial patterning that might indicate temporal cycling between different occupation zones through topographic positioning, architectural permanence, and material culture distributions.



## Results

Regional analysis revealed complex spatial organization (Fig. 1). Significant clustering emerged at all scales, with kernel density reaching 4.2 sites/km<sup>2</sup> in the central part of the Negev Highlands while extensive areas present low-density values. Sites occurred 6.45 times more frequently than expected at 500m distance, indicating highly localized aggregation. Bivariate analysis demonstrated that enclosed compounds maintained intermediate distances (2-6km) from other sites while showing attraction within 2km zones, suggesting loose territorial organization. Proximity analysis revealed strategic positioning: sites showed strong preference for arable land suitable for both pasture and opportunistic farming and natural movement corridors (albeit those have significant overlap) but, critically, no preference for permanent water sources.

At the regional scale alone, this clustering in an environmentally marginal zone with limited water access appears paradoxical for mobile pastoral populations. However, intra-site investigation revealed systematic spatial patterning that helps reframing this interpretation. Four of five sites exhibited dual seasonal zones: winter architecture on protected southeast-facing slopes utilizing natural features for shelter; and summer activity areas on exposed plateaus 50-200m distant, indicated by pottery scatters (Fig. 1). One site adjacent to the important oasis of Tell el-Qudeirat (Ben-Dor Evian 2017) diverged from this pattern, showing intensive agricultural exploitation through abundant sickle blades and dense small structures overlooking a dry stream with arable loess soils.

## Discussion

The integration of macro and micro-scale analyses reveals socio-ecological dynamics invisible at either scale independently. Regional patterns suggested intense occupation concentrated in marginal zones—seemingly maladaptive for mobile populations. Microscale investigation, however, demonstrated that individual sites were organized for seasonal cycling between protected winter locations and exposed summer areas within the same

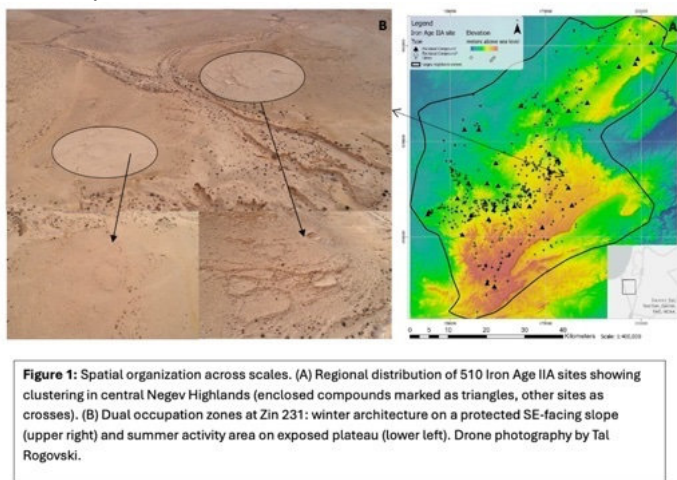
locale. This dual-zone organization indicates a flexible occupation strategy where stone-built structures served as seasonal anchor points rather than permanent residences.

Critically, the extreme clustering in the centre of the region—where environmental stability decreases moving southeast—can only be understood through a broader temporal mobility framework. In areas with lower climatic predictability, sustainable occupation requires shifting between multiple sites across the landscape, abandoning locations during poor seasons and returning when conditions improve. Investment in stone architecture at clustered sites enabled mobile households to maintain a network of seasonal bases, cycling not just between winter and summer zones within individual sites, but between different sites across seasons and years. This strategy prevented resource depletion through periodic abandonment while preserving the infrastructure for future returns, allowing participation in economic intensification (copper trade) without abandoning the pastoral mobility essential for survival in climatically inferior arid zones.

This cross-scale approach demonstrates that stone architecture in arid environments should not automatically signify sedentism in pastoral systems. The Negev Highlands case reveals how mobile populations maintained flexibility while investing in stone-built structures, balancing economic opportunities with ecological constraints through temporal rather than solely spatial risk-management strategies. The absence of water-source preference at the regional scale, coupled with evidence for seasonal movement at the microscale, indicates sophisticated adaptation to both climatic instability and economic intensification—with the high density of sites reflecting not population pressure but rather a distributed network of seasonal occupation points supporting mobile households.

More broadly, this study illustrates how integrating spatial analyses across scales can reveal human-environment dynamics in marginal landscapes where adaptation operates through temporal flexibility. By making explicit the links between local-level spatial organization and regional spatial patterns, this approach offers methodological pathways for investigating mobile societies whose adaptive strategies unfold at timeframes shorter than

traditional archaeological resolution, demonstrating ecological sustainability and resilience through cyclical rather than permanent landscape occupation in environmentally unstable contexts.



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## 89. Climate, Crisis, and Settlement Dynamics: A Quantitative Model of the Roman-Early Medieval Transition in the Moselle Valley

*Ilenia Petrarulo (University of Luxembourg)*

*Giacomo Fontana (Texas Tech University)*

This paper investigates settlement dynamics in the Luxembourg-Germany border region during the transition from Roman period to the Early Middle Ages (RM-EMA). After the end of the Roman rule, this area saw a significant rural abandonment (Van Ossel 1992), traditionally attributed solely to severe economic and social crises. However, this demographic shift coincides with a known climate crisis (Büntgen et al. 2011). This paper tests the hypothesis that climate change, in addition to socio-economic factors, played a measurable role in driving this depopulation and shaping subsequent settlement patterns.

To test this hypothesis, the study employs quantitative spatial methods, specifically point pattern analysis and point process models (Bevan 2020), to develop a diachronic comparison of settlement distribution between the 1st and 8th centuries CE. We model Gallo-Roman villas, representing the pre-crisis settlement structure, and contrast them with Merovingian cemeteries and tombs, taken as proxies for past settlement areas. These distributions, which characterize the post-crisis phase after an apparent occupational gap, are modeled against environmental variables aimed at reconstructing resources and climate conditions during the analyzed period.

We examine first-order properties of point patterns to understand how spatial intensity differs with environmental and climatic factors, fitting models separately for climate variables and a number of topographically-derived environmental covariates. By comparing climate-only models against full climate-environmental models, we can assess whether climate variables predict settlement patterns or operate through correlation with other environmental factors, such as soil type or topographic position. Environmental

variables were derived from the DEM, while climate data were obtained from the CHLSA-TraCE21k (Kargen et al. 2023) and OWDA (Cook et al. 2015) datasets.

This approach aligns with a broader methodological shift in archaeology toward modeling the human response to environmental variability, rather than simple reconstruction. The primary research goal is thus to develop a quantitative methodology that effectively integrates high-resolution climate data into the analysis of human-environment interactions. Point process models allow us to test whether observed settlement patterns reflect environmental preferences or random spatial processes, evaluating the entire landscape in order to model why certain locations were selected over others.

Although the work is ongoing, preliminary results provide insights into the complex interplay of climatic and social factors during this transitional phase. The findings offer a scalable framework for comparison with historical developments that unfolded across the European continent following the end of Roman rule.

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## 105. Trading Mediterranean summers for northern winters - studying hominin subsistence behaviour during the first occupation of northwestern Europe

*Jan-Olaf Reschke (CNRS)*

*Carolina Cucart-Mora (CNRS)*

*Kamilla Lomborg (CNRS)*

*Matt Grove (University of Liverpool)*

*Christine Hertler (ROCEEH)*

*Marie-Hélène Moncel (CNRS)*

One of the most studied aspects of hunter-gatherer behaviour is how they interact and adapt to local resource availability throughout the year. By studying recent hunter-gatherers, several behavioural strategies, in terms of how they adapt their subsistence behaviour and mobility pattern, have been identified (Kelly, 1983). Yet it still remains debated if or how actualistic approaches can be applied to the behaviour of early hominins. Estimating the variability of early hominin behaviour from the archaeological record is challenging, especially for the Early and early Middle Pleistocene when signs of hominin activity are rare to find. As part of the LATEurope ERC project, which wants to identify the constraints behind the seemingly late first hominin occupation of Europe, we want to study how early hominins may have reacted to the variety of environments they encountered when first occupying northwestern Europe.

We developed an agent-based model to simulate how foragers adapt to changes in the available plants to gather and animals to exploit using a central-place foraging approach (Reschke et al., 2024). The model allows experimenting with varying environmental conditions using reconstructed monthly net-primary productivity to derive the availability of edible plants and reconstructed animal populations to assess the occurrence of potential prey animals. In our experiments, the foragers only actively scavenged

carcasses of larger herbivores due to the limited evidence for hunting during the Early Pleistocene. We tested several subsistence scenarios, which have the group acquire meat in varying proportions. We focus on observing changes in the spatial behaviour represented by home-range as it illustrates how the foragers move across the landscape in reaction to resource availability and employed subsistence strategies. Analysing home-range, as a representation of occupied space, allows making some predictions about the connectivity between groups in the wider region which can inform large-scale processes like population dynamics and long-term viability (Mandryk, 1993).

We already presented first results after simulating hominins foraging in the Guadix-Baza Basin under both interglacial and glacial conditions at the CAA 2025. Now we present new results from additional studies of sites located in northwestern Europe and analyse the effect of latitude on resource availability. We showcase how, in terms of resource availability, early hominins in northwestern Europe encountered increasingly more hostile conditions when moving to higher latitudes. This is mostly due to the decrease in plant availability, which further decreases under glacial conditions, forcing the hominins to rely increasingly on meat. The lower resource availability forces the foragers to move more frequently and exploit larger areas. Further analysis of the results will provide new insights into the long-term viability of a given hominin population. We intend to use the novel results generated by our local-scale model within the LATEurope project as one component of a larger nested modelling approach.

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## 118. Paleoenvironmental reconstructions of the Early and early Middle Pleistocene as a scene for “Out of Africa” dispersals

*Kamilla Lomborg (CNRS UMR 7194 HNHP Institut de Paleontologie Humaine)*

*Nicolas Viovy (Laboratoire des Sciences du Climat et de l'Environnement)*

*Carolina Cucart-Mora (CNRS UMR 7194 HNHP Institut de Paleontologie Humaine)*

*Jan-Olaf Reschke (CNRS UMR 7194 HNHP Institut de Paleontologie Humaine)*

*Christine Hertler (Senckenberg Research Institute)*

*Marie-Hélène Moncel (CNRS UMR 7194 HNHP Institut de Paleontologie Humaine)*

The timing and direction followed by early hominins during the first “Out of Africa” have been questioned for decades. Computational environmental reconstructions are useful tools for investigating how climatic and environmental factors influenced the timing and routes of dispersals. Using climatic and environmental emulators as our main tools, large-scale reconstructions can be built to represent changes in past climate and vegetation. The continental scale of such reconstructions is useful for investigating the global dispersal pattern of hominins, as demonstrated in simulation studies which combine environmental reconstructions and dispersal simulations (e.g., Romanowska et al. 2017). However, the availability of environmental

reconstructions of the Early and early Middle Pleistocene is limited, despite being vital for understanding the first “Out of Africa” dispersals.

The ERC LATEurope modelling team presents novel paleoenvironmental reconstructions consisting of net primary production (NPP) and plant functional type (PFT) distribution maps, covering Africa and Eurasia in the period from 2 Ma to 0.5 Ma. The reconstruction parameters NPP and PFT have been selected as proxies for vegetation and food resources, whose influence on hominin populations have been proved through hunter-gatherer foraging theory and simulation studies.

The paleoenvironmental reconstructions presented use the Paleo-PGEM series as climatic input, a data set providing global climatic estimates for the last 5 million years (Barreto et al, 2023). From this repository four parameters have been selected and used as forcing data in the land surface model ORCHIDEE, which calculates the interactions between water, nitrogen and carbon cycles, to generate spatiotemporal specific reconstructions of the vegetation (Krinner et al, 2005). The climatic parameters have been selected due to their dominant influence on the terrestrial biosphere. After technical preparation and spatiotemporal cropping of the climatic data, they are run in ORCHIDEE, generating outputs of grid-based maps consisting of 1° x 1° pixels (approximately 12,400 km<sup>2</sup>), which contain either an NPP value or the dominant PFT category. The reconstructions represent selected time slices, which represent the most severe climatic conditions within the MIS stages of this period (MIS14-MIS75), i.e. displaying the coldest millennia in glacials and warmest millennia in interglacials. The time slices reflect of the extreme in vegetational changes, which could cause the strongest influence on hominin populations. Moreover, a strategy is developed and presented, to enable comparison of the simulated reconstructions against pollen data from matching timeslots, to evaluate the reliability of the outputs.

Considering the continental scale of the first “Out of Africa” dispersals, NPP and PFT are valuable parameters for testing environmental influences on the

population’s potential growth and expansion, especially considering that the archaeological record provides us with extremely patchy information in terms of space and time. With reconstructions capturing the environmental extreme of the MIS stages, we can observe environmentally induced changes in ecological corridors. The latest attempt of modelling this process was by Romanowska et al (2017), who suggested a connection between different biomes and hominin dispersal patterns. However, the study calls for more detailed environments. This request is now being addressed using both state-of-art climatic data and a complex land surface model. The paleoenvironmental reconstructions are a part of the nested modelling approach by the ERC LATEurope project, which is investigating the later occupation of western Europe during the Early to early Middle Pleistocene. The reconstructions contribute with a supra-continental element to this multi-layer process.

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## 122. Clean Romans, Dirty Air, and Trimmed Forests: The environmental impact of Ancient Baths

*Marta Galindo Diaz (KU Leuven)*

*Jeroen Poblome (KU Leuven)*

*Bart Muys (KU Leuven)*

*Dirk Saelens (KU Leuven)*

During the Roman Imperial period, more cities came about, and most existing ones expanded. The development of urban monumental architecture and infrastructure was actively promoted. The construction and operation of these relied on the availability and workability of diverse raw materials, including wood, clay, and stone, which were used for structural purposes, while wood also served as an energy source. The low efficiency of ancient kilns largely increased fuel requirements and emissions associated with brick, tile, and mortar production. Furthermore, the operation of buildings was energy-intensive, especially the active bath culture in the *thermae* consumed vast amounts of wood to heat rooms and water, creating additional pressure on natural resources. Such reliance on wood likely led to environmental challenges, including air pollution and overharvesting of forests, potentially leading to habitat loss and erosion. Today, environmental assessment tools allow us to systematically evaluate the impacts of the construction industry and the usage of buildings. Among them, Life Cycle Assessment (LCA) provides a structured framework for quantifying environmental and health impacts across the different life stages of a building from its construction to its end of life. However, the application of LCA tools to investigate the impact associated to the construction and usage of buildings in the past remains unexplored. This study performs a Life Cycle exercise to investigate the environmental consequences of the construction and operation of a large Bath-Gymnasium in Asia Minor during the late 1st and early 2nd centuries CE.

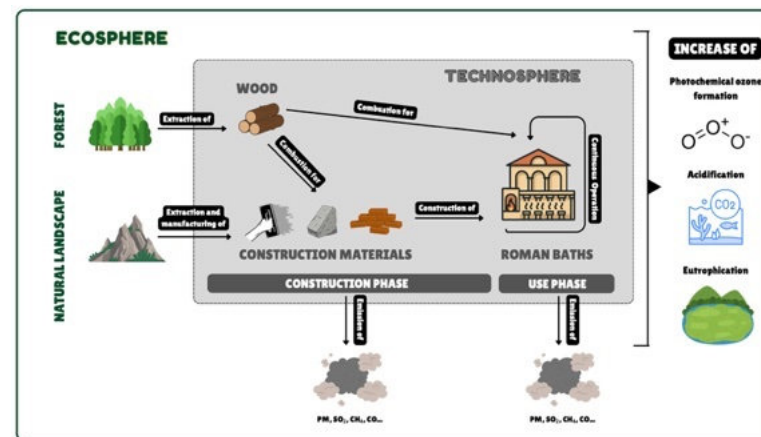
In LCA assessments, all resource and emission flows across each phase of the building under examination that are required for the completion of each stage of the building's life cycle – such as construction, operation, or end-of-use – need to be identified. Subsequently, existing methods linking extractive activities and polluting emissions are employed to quantify environmental and health impacts across different impact categories. Impact categories include climate change, land use and land cover changes, eutrophication, human and ecosystem toxicity, or depletion of natural resources. By assessing all life cycle stages and a wide range of potential impacts, the LCA methodology can be used to compare different systems and to identify whether the environmental burden has shifted from one stage to another or between impact categories. The selection of the LCA method is particularly important as this defines which impact categories will be assessed. In this study, the EN 15804 A2 method has been applied. Unlike other methods with broader applicability, such as ReCiPe2016, EN 15804 A2 was specifically developed for the assessment of buildings. In total, sixteen impact categories (e.g., land use, climate change, particulate matter, and human toxicity) were investigated. This method was employed using SimaPro software and the Ecoinvent-3 database, popular tools within LCA studies. Existing resource and emission flow databases used in current LCAs, were expanded to include processes representative of ancient socio-economic practices. To assess emissions associated with the combustion of wood for lime and mortar production, a literature review – particularly of studies in experimental archaeology – was conducted to evaluate brick production methods, kiln efficiency, and the release of key pollutants (e.g., particulate matter, SO<sub>2</sub>, CH<sub>4</sub>, and CO). Furthermore, estimates from a previous Building Energy Simulation (BES) model were used to determine the annual wood consumption required for the operation of the baths. These data were used as inputs in the EN 15804 A2 models to quantify the associated environmental impacts.

The impact associated with the use phase of the building was significantly higher compared to its construction stage. During the use phase, the highest impacts observed were those associated with photochemical ozone



formation, acidification, and eutrophication. On the other hand, the overall impact of the construction phase was lower although the same categories remained the main contributors. When comparing the different building materials, the production of lime is found to be the most detrimental manufacturing activity for the environment. To conclude, ancient monumentalization had significant environmental impacts, both due to the construction of large buildings and to the dependence of buildings such as Roman thermae on wood as an energy source, which had to be extracted, leading to deforestation, and burned, resulting in the emission of pollutants.

This research demonstrates the feasibility of applying modern tools to model the environmental impacts of ancient socio-economic activities such as the building industry. The methodology presented here could be applied to any other ancient construction for which architectural plans are available. Additionally, LCA studies are valuable not only for assessing building impacts but also for evaluating other activities, such as cooking, agricultural practices, or artisanal activities. Moreover, by adapting modern LCA tools to an ancient context, this research not only sheds light on the environmental impact of Roman urbanism but also demonstrates the value of interdisciplinary approaches in bridging archaeology and sustainability science to investigate aspects such as growth, resource procurement, and potential implications for human health.



## 234. Bottom-up or top-down? Modelling natural administrative divisions in Final Iron Age (11th-13th century) Estonia

Kristo Siig (Tallinn University)

Kaarel Sikk (Tartu University)

In Estonian landscape archaeology and historical geography, prehistoric political territories and administrative districts are mostly thought to have emerged through voluntary bottom-up integration and through an environmentally determined way – neighbouring settlements and settlement areas integrated with each other to form larger districts separated from each other by natural frontier zones consisting of forests and wetlands. This stands in contrast with the early historical period (starting from the 13th century) when the political borders and territories did not always follow natural frontiers and are known from written sources to have been formed in a top-down way through conquests and treaties. Recent studies, however, have suggested top-down integration of territories in late prehistory as well.

The current paper aims to model what the late prehistoric political map would look like in the case of organic, bottom-up integration in a deterministic way. This will be used as a null model to compare empirical data from early historical (1st half of 13th century) sources. Significant deviation from the null model will be interpreted as possible traces of political events and top-down administrative decisions from the period before written sources.

To build this null model, the paper develops and tests an explicit modelling workflow designed to explore how territorial structure might arise from local residential location choices. The primary historical dataset is the Danish Census Book (*Liber Census Daniæ*), which provides both village locations and early administrative boundaries for the early 13th century. First, a late prehistoric paleolandscape is reconstructed with particular attention to hydrology and wetland extent, as these features strongly shape natural communication routes but have changed because of the land drainage systems after the onset of large-scale agriculture. Second, village location choice is modelled through environmental suitability, assuming that social preferences do not completely overrule basic ecological constraints. Third, alternative spatial point-process models are compared to assess which generative patterns best reproduce observed settlement distributions. Fourth, the resulting settlement surfaces are used for spatial clustering to infer emergent administrative districts. This step draws conceptually on the historically attested hierarchy of dominant farms, densification patterns around strongholds, and the emergence of parish-like units. A training–testing setup based on data from two regions is used to evaluate model coherence.

Finally, these organically derived territorial clusters are compared with the documented early 13th-century boundaries. Divergences between the deterministic bottom-up model and historical reality highlight areas where political events, consolidation processes, or top-down administrative restructuring may have reshaped earlier territorial landscapes. The approach thus provides a structured way to isolate historically meaningful deviations from

environmentally expected patterns and to open the late prehistoric political geography of Estonia to systematic modelling and interpretation.

### 236. The ecological impact of early fishing: between ceramic hunter-gatherers and early farmers in the Southern Buh river valley (Southern Ukraine)

*Dmytro Kiosak (Leibniz Zentrum für Archäologie)*

The ecological impact of the spread of early farming into regions densely inhabited by hunter-gatherers remains an open research question. Evidence suggests that early farmers readily engaged in non-agricultural activities—such as fishing and hunting—when they entered landscapes well suited to these practices. The Southern Buh valley, with its rich fisheries, was likely one such region. Here, early farming potsherds appear in the same cultural layers as the remains of ceramic-using hunter-gatherer groups, which likely reflects the farmers’ participation in local fishing activities. This paper presents an effort to model this shift, interpreting the farmers’ adoption of non-farming, likely seasonal, activities as a broadening of their adaptive strategies within an unfamiliar environment.

### 252. Generative Inference and Reflexive Modelling: Bridging Scales in Socio-Ecological Archaeology

*Martin Hinz (Institute of Archaeological Sciences, University of Bern)*

*Sophie C. Schmidt (Institute for Pre- and Protohistoric Archaeology, Kiel University)*

Archaeological research increasingly seeks to understand how human–environment interactions unfolded across different spatial and temporal scales. Yet the evidence available to us — ranging from site-level stratigraphies and regional pollen diagrams to continental datasets of radiocarbon dates —

captures these scales in uneven and distorted ways. Aggregating local observations into regional or continental syntheses offers breadth but risks losing the mechanisms that generated the observed patterns. This is especially true for SPD-based reconstructions of past demographic changes (Crema 2022). Conversely, process-based simulations such as agent-based models reproduce behavioural detail but often remain empirically unconstrained. Bridging this disconnect calls for models that make cross-level linkages explicit, linking processes that operating at different observational and organisational levels, and showing how local actions generate regional outcomes and as well as how large-scale environmental trends feed back into local contexts.

In this talk we propose to use generative inference as a way to bridge these perspectives. It is an inferential framework that reconstructs the data-generating processes underlying the archaeological record. In contrast to purely descriptive statistics, generative inference treats modelling as an iterative experiment: a hypothesis about how data arise is formalised, used to generate synthetic datasets, and evaluated against observed evidence. This process is inherently generative (comparable to simulation) but remains grounded in empirical data and explicit about uncertainty (Crema 2025; Kandler 2015). In Bayesian terms, the model generates plausible histories given the data: prior → model → simulated data → comparison → posterior.

#### The problem of scale and transformation

Human–environment systems operate across multiple, interconnected scales. Human actions are implemented locally in time and space, but they are embedded within and have the potential to influence environmental processes that operate over broader and longer scales. At the same time, environmental changes at a larger scale influence local patterns, which in turn influence human behaviour. Archaeological and environmental data, however, do not map neatly onto these scales. Every observation and every proxy embodies its own spatial and temporal resolution. As these data are aggregated, transformed, and re-contextualised, the relationship between process and pattern becomes opaque. The archaeological and environmental

record can be treated as a cascade of transformations (formation, preservation, discovery, analysis) each filtering and reshaping micro-processes into macro-patterns.

This perspective implies that the data used for reconstructions contain micro-perspectives: uncertainties, resolutions, and biases that reflect their specific transformation histories. Instead of treating these as noise, generative inference models them explicitly through hierarchical observation models. Each region contributes its own likelihood; together these local likelihoods inform overarching estimates, while regional parameters constrain continental-scale reconstructions. Under this specification, macro-patterns are inferred as consequences of heterogeneous micro-evidence, rather than products of averaging.

#### Generative inference and reflexive modelling

Following Crema (2025), generative inference conceptualises statistical modelling as a process-based reconstruction of plausible pasts. It differs from classical curve-fitting approaches by embedding theory within explicit observation and measurement models. Bias and uncertainty become structured components of the model, describing how traces are transformed into data. Bayesian frameworks facilitate this structure by allowing uncertainty to propagate through all hierarchical levels and by enabling posterior predictive checks that evaluate model realism.

Such modelling is reflexive in practice: it makes explicit the assumptions linking data, process, and theory, aligning with broader calls for transparency and reproducibility in computational archaeology (Marwick et al. 2018; Cortell-Nicolau et al. 2025). Reflexive models function as epistemic artefacts that articulate how archaeological knowledge is produced. By encoding theoretical assumptions in model structure and treating bias as information, they transform uncertainty into an analytic resource. Modelling uncertainty explicitly enables a critical perspective on measurements and derived statements alike.

### Scaling and regionalisation

Because generative inference models the relationships among nested data levels, it inherently supports both up- and down-scaling.

Upscaling aggregates site-level likelihoods into regional or continental trajectories while maintaining the contribution of individual observations.

Downscaling uses posterior distributions from higher levels to generate expectations for local contexts.

This structure allows the development of regionally distinct but methodologically coherent models, each defined by local (hyper-)parameters but embedded in a shared inferential framework. Scaling thus becomes an explicit, testable operation rather than an artefact of averaging. The ongoing large-scale demographic modelling project ESTER uses a framework on a continental scale, integrating radiocarbon, typological, dendrochronological, and palaeoenvironmental proxies. Here these principles enable a coherent reconstruction of population dynamics that remains sensitive to local variation and uncertainty.

### A model ecology across scales

Generative inference does not compete with process-based simulation; it complements it as part of a pluralistic set of modelling approaches. Inference offers empirical grounding and quantification of uncertainty, whereas simulation provides mechanistic exploration of behaviour and feedback. Iteration between the two allows parameter spaces to be constrained and causal hypotheses to be tested from multiple directions. Bridging micro and macro scales, therefore, is not achieved by a single model type but by dialogue between complementary approaches operating at different levels of abstraction.

### Implications and contributions

The generative-inference perspective offers several contributions relevant to socio-ecological archaeology:

Inference as generative modelling. Statistical models act as data-driven simulations, exploring the plausible processes that produced observed patterns. Micro-information within macro-frameworks. Hierarchical structures allow site-level uncertainty to influence large-scale inference, integrating micro-perspectives rather than suppressing them.

Scaling as an explicit design choice. Up- and down-scaling can be formalised and evaluated within a single model structure, enabling transparent regionalisation.

Reflexivity as epistemic transparency. By treating bias and uncertainty as structured elements, generative inference clarifies how evidence is translated into interpretation.

Through these elements, generative inference frames modelling as an epistemologically explicit practice, one that connects human actions, environmental feedbacks, and the fragmentary traces they leave behind. This framing facilitates analysis of how local processes co-produce regional and global dynamics, while simultaneously revealing how archaeological practice itself generates knowledge from incomplete evidence.

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## 418. Modelling and simulation of mixed production and community energy balance in the Neolithic: the Cueva de la Dehesilla case study

*Juan Antonio Fernandez Morales (Universidad de Sevilla)*

*Jesús María Barandica Fernández (Universidad Complutense de Madrid)*

*Daniel García Rivero (Universidad de Sevilla)*

### 1. Introduction

The articulation of agriculture and herding is a defining feature of the earliest farming communities in Europe. Beyond identifying which crops and herds were present and where they were practiced, key quantitative questions remain: how much was cultivated, which combinations of farming and herding were most efficient, and what the effective carrying capacity of different environments was. These questions have traditionally been approached through ethnographic analogy and indirect estimates—useful as guidance but insufficient to capture interannual variability, post-harvest losses, and the dynamic nature of Neolithic agropastoral systems.

This paper proposes an alternative route based on dynamic modelling and computational simulation to quantify, in an explicit and reproducible way, the mixed economy of the first farming communities and to evaluate the viability of different subsistence strategies. We present a transferable

methodological framework that couples a crop-process simulation with a system dynamics model of community (level energy balance, with the aim of quantifying-under interannual variability and realistic losses) the per-capita requirements of cultivated surface area and livestock, and of assessing the robustness of agricultural, mixed, and pastoral strategies at Dehesilla Cave.

As a demonstrative case study we use Dehesilla Cave, a key Neolithic site in southern Iberia with a well-documented sequence and sufficient archaeobotanical, zooarchaeological, and cultural datasets to parameterize the model and appraise the plausibility of its results (García-Rivero et al. 2019).

### 2. Methods

Subsistence strategies were defined from the empirical record of Dehesilla Cave. To isolate agropastoral production (and its effect on the energy balance), we modelled strictly agropastoral economies, excluding hunting and gathering. Strategies were parameterized by the relative effort devoted to farming and herding. A community size of 45 individuals (a representative value for medium-sized Neolithic settlements) was adopted and treated as an independent variable. Three configurations, consistent with Dehesilla's phases, were tested:

- (1) Agriculture with a small herd (14 ha; 19 livestock units, LU), associated with Middle Neolithic A (first half of the 5th millennium cal BC);
- (2) Balanced mixed (11 ha; 48 LU), corresponding to Middle Neolithic B–Final (late 5th millennium cal BC); and
- (3) Pastoral with minimal cultivation (5 ha; 98 LU), consistent with the Early Neolithic (second half of the 6th millennium cal BC).

The simulation framework couples two complementary programs: Agricultural Production Systems Simulator (APSIM) for crop production (Holzworth et al. 2014) and STELLA for community-scale energy dynamics (Sterman 2000). They operate sequentially, linking plot-level yields (kg/ha) to net community caloric availability and human and herding demand.

In APSIM, the wheat module was used to simulate annual production under conditions compatible with the Neolithic. A cultivar close to *Triticum aestivum/durum* was grown under rainfed conditions with biennial fallow (alternate fallow), manual tillage, and moderate manuring. Soil data were taken from the immediate surroundings of the cave (SoilGrids), and climate data from a 40-year series for the area, used as a proxy for interannual variability; recent decades were excluded to avoid a modern warming bias. The result is a time series of yields capturing high- and low-productivity years, moving beyond the use of single mean values.

APSIM yields were exported to STELLA, a dynamic modelling environment based on stocks and flows that numerically solves discretized differential equations. In our model, stocks represent reserves of food/energy and flows regulate their temporal variation through deterministic and probabilistic rates. We adopted a weekly time step over a 40-year horizon to represent accumulation, consumption, and losses with sufficient granularity.

### 3. Results

The results show how the three strategies perform:

- Agriculture with a small herd (14 ha; 19 LU, Middle Neolithic A): deficits in 8% of simulations. When they occur, they are brief (lasting days, not exceeding one week).
- Balanced mixed (11 ha; 48 LU, Middle Neolithic B–Final): deficits in 13%, also brief (generally < 1 week).
- Pastoral with minimal cultivation (5 ha; 98 LU, Early Neolithic): deficits in 74%, with prolonged episodes that in some cases exceed one month.

### 4. Discussion

Under rainfed conditions and realistic losses, agriculture provides high caloric efficiency but is sensitive to sequences of poor harvests; herding offers relative stability (milk, strategic slaughter) and diversifies macronutrients (protein and fat), acting as a buffer. In this context, mixed strategies emerge as robust configurations: they accept a slight increase in the probability of

deficit relative to the agricultural strategy but gain in reduced per-capita cultivated area and resilience to interannual variation consistent with archaeological interpretations of diversified economies. Although cultivation is, on average, more efficient in caloric terms, livestock remains structural due to its nutritional quality, buffering capacity, and lower immediate dependence on short-term weather shocks; thus, agropastoral diversification was not only viable but a recurrent condition of stability in the earliest farming economies of southern Iberia.

The central aim is methodological: the integrated model constitutes the primary result, providing a reproducible infrastructure to convert plot yields into comparable community-scale magnitudes. Its main value is heuristic: rather than supplying closed answers, it enables the exploration of plausible hypotheses, the quantification of assumption effects, and the explicitation of premises about past human behaviour.

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## Thursday

### S1: Hic sunt dracones? Link 'em all! Linked Open Data, Wikidata and CIDOC CRM in Archaeology

*Florian Thiery, Leibniz-Zentrum für Archäologie (LEIZA), Mainz, Germany & Research Squirrel Engineers Network*

*Martina Trognitz, Austrian Centre for Digital Humanities (ACDH), Austrian Academy of Sciences, Vienna, Austria*

*Stephen Stead, Paveprime Ltd, Purley, United Kingdom*

*Daria Stefan, TU Wien, Vienna, Austria*

**Location:** Hörsaal 01

**Session Format:** Standard

Today, the World Wide Web (WWW) enables researchers to share their data, allowing the wider community to participate in scientific discourse and generate new knowledge. However, much of this shared data is neither findable nor accessible, resulting in gaps in the web map. Historical maps used the phrase 'Hic sunt dracones' (Latin for 'Here be dragons') to denote areas unknown to the mapmaker. Similarly, our modern 'unknown data dragons' lack connections to other datasets — they are not interoperable and, in some cases, unusable. To overcome these shortcomings, Linked Open Data (LOD)

(Berners-Lee, 2006; Hyland et al., 2013) techniques, as part of the wider Semantic Web, and Linked Open Usable Data (LOUD) (Sanderson 2019), can be used.

LOD and LOUD represent a way to provide data that adheres to the FAIR principles (Wilkinson et al., 2016), which were introduced in 2016. The acronym stands for Findable, Accessible, Interoperable and Reusable research data and metadata. To allow for greater interoperability and compatibility of digital datasets, CIDOC CRM (2024) and its extensions have established themselves as a de facto standard for digital archaeology data. A last puzzle piece to help in finding and linking all the data dragons are Wikibase instances, such as Wikidata, which entered the world in 2012 (Vrandečić and Krötzsch, 2014).

Semantic Modelling and LOD are a core part of Computational Archaeology and also an essential part of the FAIRification and Research Data Management (RDM) process inside the Research Data Lifecycle (e.g., Thiery et al., 2023; Schmidt et al., 2022; Thiery et al., 2023b; Thiery and Thiery, 2023; Panagiotopoulos and Trognitz, 2025). Interlinked LOD, plays a significant role in Open Science and gains more and more importance as a backbone for international and interdisciplinary RDM initiatives, such as the German National Research Data Infrastructure (NFDI), the European Collaborative Cloud for Cultural Heritage (ECCCH) or ARIADNEplus.

The Semantic Web offers a variety of vocabularies, ontologies and reference models that can be used for archaeology-related LOD modelling: CIDOC CRM, SKOS, PROV-O, FOAF, GeoSPARQL, Wikidata, etc. The Linked Data Cloud (McCrae et al., 2025) already provides FAIR and LOUD research data repositories, data hubs and domain-specific ontologies for specific archaeological and humanities domains such as Nomisma, Kerameikos, Pelagios, OpenContext, Portable Antiquities Scheme, ARIADNE, Linked Open Samian Ware, Linked Open ARS, Linked Open Ogham, and the Ceramic Typologies Ontology.

To enable non-experts to engage with FAIR and LOUD data, research tools – little minions – were created for different purposes, such as modelling relative chronologies in RDF, modelling and reasoning on vague edges in graph data, creating annotated texts and images, and SPARQL, as well as enhancing Geo-Datasets using, e.g., the SPARQLing Unicorn QGIS Plugin. In addition, community-driven knowledge bases like Wikidata not only offer data but also provide several tools for using and interacting with it.

Our session aims to bring together experts and colleagues interested in learning about FAIR and LOUD data-driven publishing and applications, as well as collecting research application scenarios to promote research domain-specific solutions for research data management. We would like to discuss application-oriented and data-driven investigations into improving technologies for FAIR and LOUD data models as a basis for reproducible and CAREful research and exchange on the Semantic Web, as well as solutions related to one or more of the issues listed below:

- application of Semantic Web technologies, such as ontologies (e.g. CIDOC CRM) or RDF/RDF-star, to the archaeological domain
- modelling of archaeological artefacts, the archaeological context, including the specificity of stratigraphy, uncertainty, and vagueness
- development of research tools producing or using FAIR and LOUD data
- interlink other data modelling concepts to semantic techniques, e.g. LPGs, HINs, FAIR Digital Objects
- computer vision or machine learning applications built upon semantic data
- building up Knowledge Graphs by applying semantic and Artificial Intelligence (AI) technologies
- modelling comprehensible/reproducible workflows and data flows using RDF/RDF-star for documentation and reproducible research
- use of LOD tools in archaeological research, their implementation and/or enhancement

- possibilities, challenges, benefits and risks of the Wikimedia Universe (e.g. Wikidata, Wikibase instances, Wikimedia Commons) in archaeological research
- implementation of reference models such as CIDOC CRM in real-world datasets and ways to achieve LOD
- graphs of facts, beliefs, and/or assertions as a digital archaeological method
- reasoning with heterogeneous and real-world archaeological data in graphs
- graph and RDF/RDF-star representation of specific networks of persons, objects and information relating to research questions
- LOUD techniques as a solution for information and data annotation on objects/artefacts in 2D and 3D (e.g. cuneiform tablets, ogham stones, samian ware, books, texts, ...)
- implementation of GeoSPARQL as a geospatial standard in archaeological data
- overcoming linguistic barriers and increasing accessibility through LOD and LOUD principles
- implementing the CARE principles through a thoughtful application of LOD and LOUD principles
- development of educational or Open Educational Resources (OERs) to increase the use of LOD

We encourage presenters to describe the problems addressed based on real-world datasets and to formulate proposals for solutions, preferably demonstrating (prototypes of) realised data-driven (web-) applications. Due to the thematic relevance, we target a broad and diverse audience, and the challenges described should also be integrated into an archaeological context (excavation, museum, archive, etc.).

This session is organised by the **CAA SIG on Semantics and LOUD in Archaeology (SIG Data-Dragon)**. The core aim of this SIG is to utilise the SIG format to raise awareness of Linked Data in archaeology by creating a friendly and

open platform for discussing and further developing semantics, as well as LOUD and FAIR data in archaeology.

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| <b>08:30 – 08:50</b> | 247. Conceptualizing Archaeological Data: A LOD-based representation of Göbekli Tepe<br><i>Antonia Lourentzaki (TALOS-AI4SSH, UOC); Maria Papadopoulou (TALOS-AI4SSH, UOC); Christophe Roche (TALOS-AI4SSH, UOC)</i>                                  |
| <b>08:50 – 09:10</b> | 14. A semantic data model based on CIDOC CRM for Mesolithic footprints analysed with a multi-method approach<br><i>Laura Albers (FAU CDI); Andreas Pastoors (FAU Erlangen-Nürnberg)</i>                                                               |
| <b>09:10 – 09:30</b> | 199. Dating the Roman conquest of Germania with Samian? Open and FAIR approaches when ordering the chronologically sensitive Arretine terra sigillata Services I-II<br><i>Allard Mees (LEIZA); Florian Thiery (LEIZA); Barbara Pferdehirt (LEIZA)</i> |

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| <b>09:30 – 09:50</b> | <p>175. Using ArchaMap to Solve a Key Problem in Re-using Archaeological Data: Linking Sites across Datasets</p> <p><i>Daniel Hruschka*; Robert Bischoff*; Matthew Peebles*; Harsha Kasi*; Sharon Hsiao (Santa Clara University)</i></p> <p><i>* Arizona State University</i></p>                                                                                                                                                                                                                                                                                                                    |
| <b>09:50 – 10:10</b> | <p>321. FAIRification of Projectile Point Typologies through ArchaMap and Wikidata</p> <p><i>Robert Bischoff*; Daniel Hruschka*; Matthew Peeple*</i></p> <p><i>* Arizona State University</i></p>                                                                                                                                                                                                                                                                                                                                                                                                    |
| <b>10:10 – 10:30</b> | <p>96. Crosswalking the Dragons: Ontologies and Metadata within the interoperable federated Cultural Heritage Knowledge Graph Ecosystem</p> <p><i>Anja Gerber (Klassik Stiftung Weimar); Florian Thiery (Leibniz-Zentrum für Archäologie (LEIZA)); Sarah Wagner (FAU Competence Center Research Data and Information (FAU CDI)); Mattis thor Straten (Kiel University); Steffen Strohm (Kiel University); Fiona Schenk (Johannes Gutenberg University Mainz); Daria Stefan (TU Wien); Andreas Noback (Technical University of Darmstadt); Peter Thiery (Research Squirrel Engineers Network)</i></p> |
| <b>10:30 – 11:00</b> | Coffee break                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |

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| <b>11:00 – 11:20</b> | <p>49. Federating the Dragons: Connecting Semantic and Digital Objects in the Federated Knowledge Graph Ecosystem</p> <p><i>Florian Thiery (LEIZA); Fiona Schenk (Johannes Gutenberg University Mainz); Daria Stefan (TU Wien); Megan Nichole Kasten (University of Glasgow); Andreas Noback (Technical University of Darmstadt); Peter A. Thiery (Research-Squirrel Engineers Network)</i></p> |
| <b>11:20 – 11:40</b> | <p>120. Show and tell – using demonstrators for reproducible results</p> <p><i>Ceri Binding (University of South Wales); Douglas Tudhope (University of South Wales)</i></p>                                                                                                                                                                                                                    |
| <b>11:40 – 12:00</b> | <p>53. Here Be Links: Taming the Data Dragons with OpenAtlas</p> <p><i>Bernhard Koschiček-Krombholz (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities); Nina Richards (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities)</i></p>                                                                                                                        |
| <b>12:00 – 12:20</b> | Discussion                                                                                                                                                                                                                                                                                                                                                                                      |

#### 14. A semantic data model based on CIDOC CRM for Mesolithic footprints analysed with a multi-method approach

*Laura Albers (FAU CDI); Andreas Pastoors (FAU Erlangen-Nürnberg)*

This paper discusses the development of a semantic data model for the analysis of prehistoric footprints found in caves. The initial data set consisted of metadata from 156 human footprints discovered in a cave in France. The

primary goal is to prepare the research data documented in Excel in a sustainable way paying heed to the FAIR principles (Findable, Accessible, Interoperable, and Reusable). Further data sets of footprint analyses are to be integrated later on in the project.

Despite being machine-readable, the current Excel data lacks the necessary semantic context and interconnection, which limits the ability to derive meaningful information from the extensive data set of approximately 7800 single facts (cells). To overcome these challenges, the intent is to semantically enrich and interlink the data in order to be processed ensuring it is accessible and reusable for the community.

The analytical approach combines two methodologies for knowledge generation: a morpho-metric approach that uses quantitative analysis to assess footprint characteristics, and a morpho-classificatory approach that incorporates qualitative conclusions from indigenous ichnologists. These experts provide valuable information about the characteristics of the footprints, such as the sex, age, weight, body postures and activities of the individuals who created them. Even events involving several participants having the same intention in their activity could have been concluded.

The Excel sheet includes about 50 columns detailing various parameters relevant to the footprints, including topographical specifications, identification metrics, and correlations to specific activities. To establish a robust data model, the ontology CIDOC CRM (version 7.1.3) has been employed. This ontology is meant to represent cultural objects and phenomena of the existing world and helps to integrate heterogeneous cultural heritage information (<https://cidoc-crm.org/>). The CIDOC CRM implementation as a formal language in OWL guarantees its machine readability. For the data model, concepts of the extensions of the Scientific Observation Model (CRMsci) and CRMarchaeo were added. In case of need for even more specific issues, new classes and properties were built in a project-specific ontology with the prefix “yy”.

The software WissKI (<https://wiss-ki.eu>) was developed to bring semantics and research data together, archiving it in an adequate manner. With its core functionality, the pathbuilder, it is capable to build, configure and group the semantic paths which describe the data in all necessary details in a network. Based on the Content Management System Drupal, every path has a corresponding field (bundled in masks) as an output, where the data is displayed. According to standard, semantic data is stored as triples following the RDF syntax. Every single triple has a unique ID (WissKI URI). In this way, data and semantics are stored at the same place and can be approached in a distinct manner. Export formats from the triple store are among others JSON, NQUAD or TURTLE. Since WissKI is a web-based application, the accessibility is basically ensured. It depends then on the data owner to grant and manage the data insight with the faceted user management brought by the underlying CMS.

As a main step in the development of a data model, key concepts had to be defined representing the core issues of the project including its context. These main bundles are circled blue in the figure. The footprint as the initial point of the analysis is represented by instances of the class yy:Spoor, a subclass of crmsci:S20\_Rigid\_Physical\_Feature. With the intention to represent a real world phenomenon we refer to the footprint as a materially visible physical feature with a relatively stable and invariant form. To represent the topographical context of a footprint, subclasses of the CIDOC CRM class E27\_Site were built. Semantically described in a part of relation, a yy:Spoor is located in (cidoc-crm:P59i) a yy:Spatial\_Subunit forms part of (cidoc-crm:P46i) a yy:Spatial\_Unit forms part of a yy:Cave.

Documenting research results requires documenting their generation. A crucial aspect of modeling with CIDOC CRM is representing reality through events, here mostly understood as attribute assignments (cidoc-crm:E13\_Attribute\_Assignments) that link information from knowledge generation to the research objects. Measures like assigning an ID to a footprint (yy:ID\_Assignment), measuring its size and distance to other footprints (cidoc-crm:E16\_Measurement and yy:Distance\_Measurement), determining its

status of preservation (cidoc-crm:E14\_Condition\_Assessment), making statements about its generation including deductions to its human creator and his activities (crmsci:S5\_Inference\_Making, see [https://cidoc-crm.org/extensions/crmsci/html/CRMsci\\_v2.0.html#S5](https://cidoc-crm.org/extensions/crmsci/html/CRMsci_v2.0.html#S5)) are represented via subclasses of cidoc-crm:E13\_Attribute\_Assignment (orange circled classes in the figure). The research outcome of the Inference Making represents the statements taken by consensus by the track readers (subject, activity, event and trackway).

The overall analyzing measures of each footprint are bundled by an instance of the class crmsci:S4\_Observation. It “comprises the activity of gaining scientific knowledge about particular states of physical reality through empirical evidence, experiments and measurements” (see [https://cidoc-crm.org/extensions/crmsci/html/CRMsci\\_v2.0.html#S4](https://cidoc-crm.org/extensions/crmsci/html/CRMsci_v2.0.html#S4)) All Observations analyzing single footprints take place within the archaeological project (crmsci:S4\_Observation -> cidoc-crm:P10\_falls\_within-> yy:Archaeological\_Project). In the project-specific ontology the latter is defined as a coordinated set of activities for gaining knowledge by means of different methods.

The data model is adaptable and extendible for research data focused on the documentation and interpretation of prehistoric footprints in caves. The data stored in semantic triples can be easily integrated into various data pools, regardless of their underlying structures. It also supports scenarios where multiple archaeological projects study the same footprints. A key issue is the lack of unique identifiers for footprints; establishing a UID system is crucial to ensure that different projects can accurately refer to the same footprint. WissKI offers a non-semantic URI for unique identification of each node, enabling distinct access to individual footprints and their observations.

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## 49. Federating the Dragons: Connecting Semantic and Digital Objects in the Federated Knowledge Graph Ecosystem

*Florian Thiery (LEIZA)*

*Fiona Schenk (Johannes Gutenberg University Mainz)*

*Daria Stefan (TU Wien)*

*Megan Nichole Kasten (University of Glasgow)*

*Andreas Noback (Technical University of Darmstadt)*

*Peter A. Thiery (Research-Squirrel Engineers Network)*

### Introduction

Archaeological, geoscientific, and research software engineering increasingly depend on interoperable infrastructures capable of linking heterogeneous datasets, from text and imagery to 3D reconstructions and analytical results. While the Linked Open Data (LOD) paradigm (Schmidt, Thiery, and Trognitz 2022), based on RDF, has proven effective for structured and textual information, it cannot natively represent binary or complex file types such as 3D models, high-resolution imagery, laboratory measurements, or executable research software. In contrast, the FAIR Digital Object (FDO) concept (De Smedt, Koureas, and Wittenburg 2020), widely adopted in engineering and the natural sciences, addresses such limitations by defining identifiable, citable research objects with persistent identifiers and machine-actionable metadata. Yet, connecting FDO-based artefacts with RDF-based LOD environments remains a critical challenge.



To overcome this gap, this paper explores a federated Knowledge Graph ecosystem combining three interoperable layers (Fischer et al. 2025):

- (1) a LOD layer, expressing structured, semantic relationships using CIDOC CRM, PROV-O, GeoSPARQL, and SKOS, and extending to textual corpora encoded in TEI/XML
- (2) a community layer, integrating Wikibase platforms such as Wikidata, FactGrid, Semantic Kompakkt, and fuzzy-sl Wikibase, each providing access via SPARQL or web APIs but differing in their degree of LOD compliance;
- (3) an FDO layer, storing binary and compound research artefacts — including software, 3D SfM models, and analytical datasets, described through CFF, DataCite, schema.org, or CodeMeta metadata.

Developed within a national research-data initiative related to archaeology, this work highlights software as a first-class research artefact, not merely as a FAIRification service. It aims to bridge RDF/LOD semantics with FDO principles, enabling sustainable, interdisciplinary, and reproducible Knowledge Graphs across cultural-heritage and scientific domains.

This interoperability is particularly relevant for archaeology, where linking excavation data, artefact documentation, and analytical datasets enables integrated interpretations of cultural and environmental processes. By connecting semantic models from material culture, landscape studies, and laboratory analyses, federated Knowledge Graphs can provide a new level of contextual understanding and reproducible research within digital archaeology.

#### Material and Methods

The approach presented in this paper combines semantic modelling, FAIR Digital Object practices, and Research Software Engineering (RSE) methods within a federated Knowledge Graph architecture. The ecosystem builds on three interoperable layers: a LOD layer based on RDF and CIDOC CRM; a community layer integrating multiple Wikibase instances and external data hubs; and an FDO layer providing persistent, metadata-rich representations of

digital research artefacts. Data are transformed and represented using Python-based pipelines, the SPARQLing Unicorn Toolkit, and version-controlled Git repositories that store both datasets and code as research artefacts.

A. Ogham/Govan Ecosystem. The Ogham case study demonstrates how textual, spatial, and 3D data can be integrated into a federated Linked Data environment. Epigraphic sources from the OG(H)AM project, initially encoded in TEI/XML, were mapped to CIDOC CRM classes, such as E22 Homan-Made Object. The resulting RDF graphs were interlinked with Wikidata, FactGrid, Semantic Kompakkt (for 3D annotations), and the fuzzy-sl Wikibase (for geospatial uncertainty). Binary 3D models derived from Structure-from-Motion (SfM) reconstructions, created, for instance, using the KIRI Engine or citizen-science smartphone captures, were registered as FDOs with structured metadata. Associated transformation scripts and Jupyter notebooks were likewise published as software FDOs, ensuring complete provenance and citation. The Govan case study is based on the PhD thesis “The Govan stones revealed: digital imaging in the analysis of early medieval sculpture,” which handles distributed, technology-varying 3D models (as FDOs) as well as Wikidata and OSM entries.

B. Geoscientific Data. The second case study applies the same principles to geoscientific datasets, including tephra and sediment analyses from the Eifel region and the Campanian Ignimbrite eruption deposits. Traditionally processed in Excel spreadsheet environments, these datasets were re-implemented as reproducible Python pipelines employing pandas and matplotlib. Each analytical workflow, covering EPMA and LA-ICP-MS analysis and GDGT-based temperature reconstructions, was treated as a software FDO linked to the resulting data FDOs. Laboratory outputs need to be FAIRified into RDF using domain-specific ontologies, ensuring semantic interoperability. Findspots such as Campanian Ignimbrite sites, often co-located with archaeological sites, were modelled with the fuzzy-sl Ontology to capture spatial uncertainty and linked to archaeological contexts. Together, these two case studies illustrate how heterogeneous data, binary artefacts, and executable code

can be semantically integrated into a federated, FAIR-compliant Knowledge Graph. However, the major challenge remains: how to map these diverse representations consistently to archaeology and CIDOC CRM?

### Results

The results show a prototypical implementation of a federated Knowledge Graph that interlinks heterogeneous research artefacts across LOD, community, and FDO layers. RDF graphs, harmonised through CIDOC CRM, PROV-O, and GeoSPARQL, are complemented by community-driven Wikibase instances such as Wikidata, FactGrid, Semantic Kompakkt, and the fuzzy-sl Wikibase, all queryable through federated SPARQL SERVICE requests. The prototype demonstrates that FAIR Digital Objects (FDOs), software, 3D models, and laboratory datasets, can be semantically linked to RDF entities via persistent identifiers and contextualised with RDF metadata. This ensures machine-actionable semantics while maintaining the integrity of binary artefacts. Shared SKOS vocabularies and terminology services connect domain-specific and cross-disciplinary ontologies, enabling automated alignment and provenance tracking. Together, semantic technologies, FDO standards, and RSE-driven reproducibility establish a scalable framework for integrating archaeological, geoscientific, and computational data within a single, FAIR-compliant Knowledge Graph.

### Discussion

Integrating RDF-based LOD with FDOs offers a promising yet challenging path toward fully interoperable research ecosystems. The combination of RDF triples, binary SfM models, and executable notebooks demonstrates cross-domain interoperability but also reveals technical constraints of current Semantic Web infrastructures. FDOs enable persistent identification and citation, but their seamless integration requires automated crosswalks between metadata schemas such as DataCite, CodeMeta, and CIDOC CRM. Federated SPARQL endpoints and FDO registries face performance and access challenges, calling for harmonised metadata publication and extended frameworks supporting semantic queryability. In line with the session's theme, this

work identifies the remaining “dragons” of semantic federation and points to the next step: connecting existing ontologies through automated, FAIR4RS-compliant workflows. Bridging RDF and FDO ecosystems provides a sustainable foundation for interoperable, reproducible digital scholarship across archaeology, geosciences, and research software engineering.

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## 53. Here Be Links: Taming the Data Dragons with OpenAtlas

*Bernhard Koschiček-Krombholz (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities)*

*Nina Richards (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities)*

### 1 Introduction

The increasing use of digital methods in archaeology has led to a proliferation of diverse datasets and formats. While the potential for linking and reusing

these data is immense, researchers often face a significant barrier: achieving interoperability and FAIRness requires technical and semantic expertise. For many archaeological projects, the challenge lies not in a lack of data, but in the complexity of turning them into Linked Open Data (LOD).

OpenAtlas (<https://openatlas.net>) addresses this issue by providing a flexible, open-source database environment that implements these principles while remaining accessible to non-specialists. It enables researchers to create structured, semantically rich datasets that comply with standards of the digital humanities community. OpenAtlas facilitates the structured recording of data—mapped according to the CIDOC Conceptual Reference Model (CIDOC CRM) and linked to controlled vocabularies and gazetteers (Richards et al. 2023, Eichert et al. 2024).

This paper presents OpenAtlas as a practical tool for bridging the gap between digital theory and archaeological practice. It shows how a database framework can “tame the data dragons” by simplifying FAIR-compliant data entry, ensuring interoperability, and supporting sustainable, semantically connected research infrastructures.

## 2 Methods and materials

Built on Python3 and PostgreSQL, OpenAtlas implements a semantic data model based on CIDOC CRM (ISO 21127:2023)(Richards et al. 2023).

The system defines entities such as sites, features, stratigraphic units, finds, persons, and events, which can be interlinked to represent complex archaeological contexts. Each entity is connected through well-defined relationships derived from CIDOC CRM, ensuring semantic transparency and interoperability.

OpenAtlas is designed for usability. It offers a web-based interface accessible through any modern browser. Researchers enter data via structured but flexible forms, adapted to project-specific needs through configurable “types.” This approach allows the same platform to serve various disciplines—from medieval archaeology to environmental history—without changing the underlying model.

OpenAtlas operationalizes the FAIR principles in a concrete, usable way:

**Findable:** Each entity receives a persistent URL and unique identifier, ensuring citability.

**Accessible:** Data can be accessed via the web interface or the API as (Geo)JSON or RDF.

**Interoperable:** The data model is CIDOC CRM-compliant and enriched through SKOS vocabularies, controlled thesauri, and linked gazetteers.

**Reusable:** All content and code are openly licensed (CC BY 4.0/open source), ensuring reusability across projects.

## 3 Results

OpenAtlas serves as the backbone for several major research projects combining archaeological, historical, and anthropological data.

THANADOS (The Anthropological and Archaeological Database of Sepulchres) uses OpenAtlas to document and visualize Early Medieval cemeteries across Central Europe. Each burial site, grave, and artefact is represented as an interconnected entity, allowing users to explore spatial relationships through interactive GIS maps and perform statistical analyses online (Eichert 2021).

RELIC (Modelling Religiopolitics – The Imperium Christianum via its Commoners) extends this approach by integrating historical sources, ecclesiastical networks, and social actors. Through OpenAtlas, RELIC connects burial evidence with textual and environmental data, enabling the study of Christianization and religiopolitical transformation during the 10th–12th centuries.

Both projects demonstrate how OpenAtlas transforms heterogeneous, discipline-specific datasets into harmonized, semantically structured research resources that comply with LOD standards.

By abstracting semantic complexity, OpenAtlas allows researchers to generate Linked Open Data as a by-product of their regular workflow. Data recorded through the interface can be linked to external repositories such as Wikidata or GeoNames.

OpenAtlas employs a 'semantic-native' relational design where the PostgreSQL schema is directly modeled after the CIDOC CRM object-oriented framework. Because the data is stored in a way that inherently respects the

ontology's structure, Linked Open Data is generated dynamically via a serialization layer rather than a complex Relational-to-Ontology Mapping (R2RML) process. This approach allows OpenAtlas to provide the robust data integrity and transactional consistency of a relational system while functioning as a native LOD environment. While a dedicated triple store is not used for primary storage, the system's architecture allows for a parallel triplestore integration if advanced SPARQL reasoning or cross-dataset federated queries are required

#### 4 Discussion

The metaphor of "data dragons"—isolated, unconnected datasets—aptly describes a central challenge in digital archaeology. OpenAtlas provides a pragmatic solution by offering a single environment where researchers can structure, enrich, and publish their data while automatically maintaining interoperability and semantic consistency.

By keeping technical complexity in the background, OpenAtlas makes it easier for researchers to apply FAIR and LOD principles in their work. It allows archaeological teams to create reusable, interconnected datasets without requiring specialized digital humanities skills.

Sustainability in digital archaeology requires more than long-term storage—it depends on adaptability. OpenAtlas achieves this through its modular structure and semantic model, which allows projects to evolve without breaking compatibility. The system's use across diverse domains—archaeology, history, anthropology, cultural heritage—illustrates its robustness and generalizability.

#### 5. Conclusion

OpenAtlas demonstrates that Linked Open Data and FAIR data management can be implemented in a way that is both scientifically rigorous and user-friendly. By concealing technical complexity behind an intuitive interface, it enables archaeologists to participate fully in the Semantic Web without becoming experts in data modelling.

In doing so, OpenAtlas contributes to making digital archaeology not only more connected but also more inclusive. It turns "here be dragons" into "here be data"—findable, accessible, interoperable, and reusable.

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## 96. Crosswalking the Dragons: Ontologies and Metadata within the interoperable federated Cultural Heritage Knowledge Graph Ecosystem

*Anja Gerber (Klassik Stiftung Weimar)*

*Florian Thiery (Leibniz-Zentrum für Archäologie (LEIZA))*

*Sarah Wagner (FAU Competence Center Research Data and Information (FAU CDI))*

*Mattis thor Straten (Kiel University)*

*Steffen Strohm (Kiel University)*

*Fiona Schenk (Johannes Gutenberg University Mainz)*

*Daria Stefan (TU Wien)*

*Andreas Noback (Technical University of Darmstadt)*

*Peter Thiery (Research Squirrel Engineers Network)*

### Introduction

Archaeological and cultural heritage research increasingly relies on federated data infrastructures containing heterogeneous datasets originating from excavations, collections, laboratory analyses, and research software. Within a federated Knowledge Graph ecosystem (Thiery et al. 2025a; Fischer et al. 2025), such data can be interlinked using Semantic Web technologies. Yet, the metadata describing these resources often adhere to different standards: collection data are frequently modelled with LIDO (Lightweight Information Describing Objects) or CIDOC CRM, software follows CodeMeta or CFF, and generic metadata employ DCAT, DataCite or schema.org. Achieving interoperability between these layers is a persistent challenge, especially when archaeological data meet interdisciplinary contexts.

In archaeology, CIDOC CRM has become the de facto reference model for structuring cultural heritage information and ensuring semantic interoperability. However, when used as the sole framework, it cannot fully represent the analytical or quantitative dimensions of interdisciplinary research, such as laboratory results, or research software. Consequently, domain-specific ontologies and metadata standards must be aligned through crosswalks that extend beyond traditional museum documentation.

To address these needs, e.g., initiatives within the German research data infrastructure for human remains of the last 2.6 mio. years, NFDI4Objects, develop integrated solutions for FAIR and LOUD data across the humanities and natural sciences. Central to this effort is the NFDI4Objects Knowledge Graph, which adopts CIDOC CRM as a backbone while interlinking to Wikidata and other Wikibase instances as community-driven semantic resources as well as FAIR Digital Objects (FDO). These federated components enable open collaboration, reproducibility, and shared identifiers across institutional and citizen-science boundaries.

This paper introduces two complementary frameworks for semantic alignment: the Object Core Metadata Profile (OCMDP), connecting object and software metadata to DCAT, schema.org, and DataCite; and the Material Cultural Heritage Crosswalk Ontology (MaCheCO), providing ontology-based mappings from archaeological, geoscientific, and community models (such as Wikidata) to CIDOC CRM and its extensions. Together, they support interoperable, interdisciplinary Knowledge Graphs uniting data from cultural heritage, geosciences, and computational archaeology.

The research addresses three guiding questions:

- (1) How can heterogeneous metadata be harmonised through ontology-based crosswalks?
- (2) How can collections, software, and analytical data be semantically aligned within federated KGs?
- (3) Which interoperability models best sustain reproducible, interdisciplinary research across archaeology and related sciences?

## Material and Methods

This research combines metadata harmonisation (examples A), ontology engineering (examples B) and applied semantic modelling within a federated Knowledge Graph architecture.

The OCMDP ensures compatibility with the emerging NFDI Core Metadata Profile by providing mappings to schema.org, DataCite, DCAT, and CodeMeta, thus bridging between object-oriented cultural-heritage data and research-software metadata.

A1. In the first use case, software-related metadata were modelled using CodeMeta and cross-walked to Citation File Format (CFF), Wikidata, and repository metadata (e.g. Zenodo, GitHub). This workflow demonstrates how software can be treated as a first-class FAIR Digital Object (FDO) and research artifact (Thiery et al. 2025b) within archaeological research infrastructures.

A2. The second use case applies the OCMDP to museum and collection data using the Minimum Record Recommendation (MDS v1.1) developed by the Minimum Data Recommendation Working Group. Here, collection-level metadata were expressed as RDF entities and harmonised with DCAT and CIDOC CRM concepts, enabling inter-repository querying within the NFDI ecosystem.

The MaChECo ontology extends the OCMDP by creating a semantic translation layer across multiple disciplinary standards.

B1. In the object-biography use case, excavation, collection, conservation, and analytical events were modelled as CIDOC CRM instances, forming a coherent lifecycle representation

of artefacts. Implemented within a WissKI-based KG prototype, this model demonstrates how provenance and transformation processes can be linked to OCMDP modules.

B2. The LIDO-to-CIDOC CRM mapping establishes correspondences between LIDO elements and CRM classes, enabling museums and archives to publish interoperable RDF data directly consumable by the NFDI4Objects Knowledge Graph.

B3. The Archaeo-Natural Ontology (ArNO), based on the LADO ontology from archaeology.link, will integrate archaeo-natural datasets, e.g., from the Poseidon, Arbodat+ and PANGAEA platforms, through an ontology crosswalk linking biological sample metadata to CIDOC CRM. This demonstrates how laboratory data and contextual archaeological information can coexist within a shared semantic framework.

B4. A further group of use cases explores community-curated data. Data from Wikidata, fuzzy-sl Wikibase, and FactGrid are integrated into the MaChECo ontology through semi-automated RDF pipelines. Three examples illustrate the versatility of this workflow: the Ogham Stones dataset, modelling person-tribe networks; the Irish Holy Wells project, representing ritual and spatial relations; and the Cuneiform Mathematical Tablets, linking CDLI artefacts and mathematical formulae. These mappings preserve provenance qualifiers and demonstrate cross-domain interoperability between historical, linguistic, and mathematical knowledge.

B5. Finally, the geoscientific use case links archaeological sites with geological observations, exemplified by the Campanian Ignimbrite eruption dataset. Using the Fuzzy Spatial Locations Ontology (FSL-O), spatial uncertainty and precision metadata were modelled alongside site and sampling information, thereby aligning GeoSPARQL, CRMsci, and CRMarchaeo concepts within the MaChECo framework.



Together, these use cases establish a reproducible methodology for transforming heterogeneous cultural-heritage, scientific, and community data into a CIDOC-aligned, federated Knowledge Graph.

#### Results & Discussion

The Object Core Metadata Profile (OCMDP) and the Material Cultural Heritage Crosswalk Ontology (MaCheCO) form complementary components of a federated semantic infrastructure. The OCMDP harmonises software and collection metadata through mappings to DCAT, DataCite, schema.org, and CodeMeta, while MaCheCO aligns LIDO, ArNO, Wikidata, and GeoSPARQL models with CIDOC CRM. Applied to use cases such as Ogham, Holy Wells, Cuneiform Maths, and Campanian Ignimbrite, both frameworks enable interoperable, cross-disciplinary querying and integration within the NFDI4Objects Knowledge Graph.

The combined application of OCMDP and MaCheCO shows that metadata interoperability can be achieved through federated, ontology-driven modelling. OCMDP bridges humanities- and software-based data standards, while MaCheCO ensures semantic crosswalks across archaeological, geoscientific, and community models. Together they demonstrate how FAIR and LOUD principles can be operationalised in federated Knowledge Graphs. These frameworks establish a sustainable blueprint for interdisciplinary data integration, provenance tracking, and uncertainty modelling within the broader NFDI Knowledge Graph Federation.

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## 120. Show and tell – using demonstrators for reproducible results

*Ceri Binding (University of South Wales)*

*Douglas Tudhope (University of South Wales)*

Within the ATRIUM project the reuse of datasets, tools, techniques and workflows is a common activity. Workflows have been demonstrated to provide useful description and instructions for repeated tasks. Each step of a workflow can itself be a workflow describing the individual steps to take, but at its heart it remains a set of instructions - in the previous CAA conference we made the analogy to a recipe. A valuable further addition then would be a practical demonstration of each step. This could firstly assure others that the methodology being followed is both sound and appropriate and that the results are accurate. Secondly it would provide a record of the environment and tools used and the steps taken. Thirdly it could imbue others with more

confidence when approaching the same or a similar task. How then could we translate these ideas to our own domain and environment?

Python notebooks represent one useful and powerful solution. These describe and provide the exact environment and tools used, so they can be reproduced consistently. Using open standards notebooks can incorporate code, descriptive text, data and visualisations. They contain step by step executable source code fragments showing exactly how to achieve identical results. Others can then assess, reuse, adapt, improve, fix(!), or reference all or any part of the demonstrators as required. This promotes collaboration, reproducibility and reusability of the input data, description, techniques, source code and results.

As part of the ATRIUM project we are creating a series of collaborative, educational, reusable & interactive demonstrators. These can often represent not just demonstrators, but the same working code that produced the original results. As well as being a practical demonstration of the steps of a workflow, demonstrators can also reuse other existing workflows describing how to obtain and use external datasets and may even reuse parts of other demonstrators to perform certain tasks where commonality exists. We will show examples of these demonstrators and show how they can facilitate reproducibility and reuse.

## 175. Using ArchaMap to Solve a Key Problem in Re-using Archaeological Data: Linking Sites across Datasets

*Daniel Hruschka (Arizona State University)*

*Robert Bischoff (Arizona State University)*

*Matthew Peebles (Arizona State University)*

*Harsha Kasi (Arizona State University)*

*Sharon Hsiao (Santa Clara University)*

### Introduction

The increasing accumulation of archaeological data in digital repositories (CyberSW, Open Context, tDAR, ADS) has created great potential for linking data for novel analyses. However, linking data for re-use requires reconciling complex categories (e.g., sites, artifact types, periods) that are often encoded in incompatible ways across datasets. Developing efficient and robust tools for reconciling categories across diverse datasets and sharing these translations is an important step toward re-using digital datasets. In this paper, we describe using ArchaMap address these issues using one kind of complex category—sites—across large datasets with data on radiocarbon dates (p3k14c, Kelly et al.), dendrochronology (Kohler and Bocinsky), and artifact types (CyberSW, Village Ecodynamics Project) as well as a commonly used gazetteer (Pleiades).

### ArchaMap

CatMapper's (<https://www.catmapper.org>) ArchaMap app assists researchers in making archaeological datasets interoperable by providing tools for translating complex categories like artifact types, lithics, ceramics, time periods and site contexts from diverse datasets (Hruschka et al., 2022). ArchaMap also allows users to document and share the details of past translations, supporting transparency and reusability.

ArchaMap uses a graph database to organize complex, hierarchically-structured categories, from diverse datasets. It represents each unique category

(e.g., the site “Chetro Ketl”) and dataset (e.g., p3k14c) as a node. A “Uses” tie from a dataset node to a category node captures claims that specific dataset makes about the category (e.g., alternative names, region/country, geospatial coordinates, the dataset’s url for that category). To facilitate linking categories across datasets, each “Uses” tie also stores the key used by the data source to uniquely identify that category. This structure permits: (1) efficient, bulk matching of categories from new data sources, by leveraging alternative names integrated from multiple sources (2) detecting errors by permitting comparison of contextual information across different datasets pointing to the same node, and (3) transparently indicating provenance of all claims about categories.

Once categories from a dataset are linked to ArchaMap, the app also provides tools for proposing how these categories can be merged across datasets. The most straightforward match is when two datasets have Uses ties pointing to the same category node (e.g. both point to the node for the “Chetro Ketl” site). But ArchaMap also stores information about hierarchical relationships between sites (e.g. Chetro Ketl contains “Chetro Ketl room 92”), and it can propose matches between sites across datasets that are connected by such hierarchical relationships.

Methods and Materials

We use six large datasets with data on radiocarbon dates (p3k14c, Kelly et al.), dendrochronology (Kohler and Bocinsky), and artifact types (CyberSW, Village Ecodynamics Project) as well as a commonly used gazetteer (Pleiades) (Table 1). Four of the datasets have explicit site ontologies with unique IDS. The other two (p3k14c and Kelly et al.) have columns for both site number and site name with varying levels of completeness and substantial variation in ids and names for the same sites. We exclude ~3000 records from Kelly et al. and 707 from pk314c that had neither site ID or Name nor geospatial location.

Table 1. Six datasets with site categories linked to ArchaMap.

| Dataset                        | Records | Unique Sites | Unique Site IDs |
|--------------------------------|---------|--------------|-----------------|
| CyberSW                        | 26802   | 26736        | Y               |
| Village Ecodynamics Project    | 25532   | 25407        | Y               |
| Pleiades 4.1                   | 41583   | 41582        | Y               |
| p3k14c                         | 173243  | 41231        | N               |
| Kelly et al.                   | 101650  | 25091        | N               |
| Kohler and Bocinsky tree rings | 32867   | 1127         | Y               |

Using ArchaMap’s propose translate function, we first matched cyberSW’s sites to existing ArchaMap categories based on fuzzy lexical matches with names and site ids constrained by U.S. and Mexican state (adding new sites for unmatched cyberSW sites). We then used the same process to match the village ecodynamics sites, and then the Pleiades sites. We then matched records from p3k14c using the propose translate function applied to both the site id and names columns constrained by geospatial location and then matched the Kelly et al. and finally the Bocinsky records. Error checks included: (1) identifying matches from different datasets or records that had very different geospatial locations, (2) identifying different nodes with similar names and geospatial locations as candidates for merging.

Results

Consolidating records into sites. In the two datasets that do not have explicit site ontologies, the process identified 41231 unique sites for p3k14c and 25091 unique sites for Kelly et al. Notably, in the four datasets with unique ids for sites, there were varying levels of duplication (1 in Pleiades, 125 in Village Ecodynamics, and 66 in CyberSW).

Reconciling variable site names and ids. The process identified and reconciled a great deal of variability in site names and ids, including spacing differences (e.g., “V:5: 119” vs “V:5:119”), spelling differences (e.g., 2 Baker vs Two

Baker, Tucson Mts vs Tuscon Mountains), using Names versus site numbers (e.g., L Dorothy vs 5MT10595), variation in separators and zeros (7S-K-21 vs 7SK21), likely transpositions in site numbers (10CR385 vs 10CR358 for East Fork Lookout), other mistakes in site numbers (10BM247 vs 10PR247 for Bronco Jim site), and different site number conventions (U:8:23 vs U:8:23/177, 35LNC57 vs. 35LN57, 26CX1 vs LA8121).

Finding matches across datasets. Once the site categories from all datasets were linked to site categories in ArchaMap, ArchaMap's propose merge function allows users to identify all categories shared by a combination of these datasets. For example, 316 sites have both radiocarbon dates in p3k14c and artifact data from cyberSW, and 577 sites have both tree ring dates in Kohler and Bocinsky and artifact data in cyberSW. The propose merge function also offers several ways to output these matches for linking across datasets by their keys.

#### Discussion

CatMapper/ArchaMap provides tools for overcoming key bottlenecks in linking records by complex categories—such as sites—both within and across datasets. Moreover, once such links are made, ArchaMap stores those translations for other researchers to use. Indeed, based on the work described in this paper, ArchaMap now contains translations between sites in six major publicly available datasets and gazetteers (i.e, p3k14c, lower 48 radiocarbon, Kohler and Bocinsky, CyberSW, Village Ecodynamics Project, and Pleiades).

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## 199. Dating the Roman conquest of Germania with Samian? Open and FAIR approaches when ordering the chronologically sensitive Arretine terra sigillata Services I-II

*Allard Mees (LEIZA)*

*Florian Thiery (LEIZA)*

*Barbara Pferdehirt (LEIZA)*

Dating the Roman conquest of Germania with Samian? Open and FAIR approaches when ordering the chronologically sensitive Arretine terra sigillata Services I-II

#### Introduction

Roman Samian Ware (terra sigillata) has always been thought to have been a chronologically sensitive dating material when it comes to the period in which Magna Germania was conquered BC 30 - AD 20 by the Romans. Because the terra sigillata vessel types themselves were already standardised and fabricated in antiquity by the introduction of so-called Services (similar to modern Wedgwood or Meißener porcelain), the identification of these Services themselves has never been a matter of discussion. However, due to the appearance and disappearance of these vessel type Services (Services I and II and their subvariants), it has always been thought that there is some kind of chronology behind these Services. A few dated sites suggest that vessel types of Service I may have started to be produced earlier than the Service II model series. Since occurrences in so-called dated sites have never been quantified before, there is a huge lack of traceability and verifiability behind

these considerations. On top of that, a lack of open and FAIR approaches is also hindering deepening methods on finding out whether this material is suitable for verifiable chronological studies of the Roman conquest of the new province, Magna Germania.

### Material and Methods

The material chosen here to demonstrate verifiable dating methods, resulting in FAIR and interoperable research results, is considered a core instrument for dating the conquest of Magna Germania during the reigns of Augustus and Tiberius. From today's perspective, it is surprising that the early “fathers of Roman ceramic research,” Dragendorff (1870-1941) and Déchelette (1862-1914), failed to recognise the service concept inherent in the formal repertoire of Arretine and Gallic sigillata. It is largely thanks to his contemporary, Siegfried Loeschke (1883–1956), that this ancient Service concept was demonstrated using the Haltern sigillata discovered from 1899 onwards and published in 1909 (Loeschke 1909, 136-137). This concept of Arretine Services within the repertoire of Italian-made terra sigillata was presented in a refined form in 1942 (Vogt 1948, 151). Most of the Arretine Service forms were directly incorporated into the later Gallic repertoire.

The military camp of Haltern was part of the advance of the Roman army along the river Lippe in modern-day Magna Germany. From some military camp sites, dendrodata of their construction phase are known, hence providing an additional anchoring of a relative chronology of the Arretine Services within the framework of absolute chronological dates.

The co-occurrence of relative time intervals of temporarily occupied military camps combined with absolute dates implies the application of seriations and multivariate statistics (correspondence analysis), combined with Allen's algebra algorithms. Together with the Academic Meta Tool and the exploration of the Euclidean distances within the first 3 dimensions of a correspondence analysis, statements about a temporal ordering of the military camps can be made.

### Results

A Linked Open Data (LOD) dataset will be created from the previously unpublished analogue material, transforming it into machine-actionable RDF. The dataset is modelled using the Linked Archaeological Data Ontology (LADO) — the core ontology of the archaeology.link data hub — and therefore fully aligned with CIDOC CRM and its extensions (Thiery and Mees 2024). Each record represents an occurrence of Arretine Service I–II vessel types at specific sites and is expressed as `lado:InformationCarrier` linked to `lado:DiscoverySite` entities. The dataset is designed for integration into the Linked Open Samian Ware Ontology, ensuring interoperability within the broader Linked Archaeological Data Ontology (LADO) framework and the NFDI4Objects Knowledge Graph ecosystem. An RDF dataset of the Allen Interval Algebra has been generated using the Alligator Method, implemented via the Alligator – Allen Transformer. This dataset provides a semantic representation of the relative chronological relations (e.g., before, during, overlaps) between Arretine Services and their occurrences in military camps, which are for several reasons suspected to have been occupied during a limited time interval.. Each temporal relation is encoded using OWL-Time properties (e.g., `time:intervalBefore`, `time:intervalOverlaps`) and linked to the underlying correspondence analysis output. The resulting RDF graph enables reasoning over temporal relations through the Academic Meta Tool (AMT), allowing reproducible FAIR workflows and seamless integration into LADO-based Knowledge Graphs.

The combination of technologies—the AMT tool, correspondence analysis, and Allen's algebra algorithm—yields results that enhance the chronological classification of military camps, including those without dendrochronological evidence. The results deeply improve our chronological views on the conquest of Roman Magna Germania.

### Discussion

This paper presents new chronological insight into the Roman occupation of Magna Germania during the principate period. It can be discussed how the relative ordering of the chronologically sensitive evidence of Samian Services I-II evidence relates to the absolute historical known time intervals of the

conquest of Magna Germania. This research starts a discussion on the chronological relevance of Arretine terra sigillata related to frameworks of dendrochronological datings and how advanced FAIRification tools enable interconnections between both archaeological phenomena.

The implementation of these LOD models demonstrates how traditionally analogue archaeological datasets can be FAIRified and semantically integrated within domain-specific infrastructures such as archaeology.link. By embedding the resulting RDF datasets into the Linked Open Samian Ware Ontology, this work contributes to a federated semantic network of Roman ceramic data interoperable with the NFDI4Objects Knowledge Graph. Beyond methodological innovation, this approach exemplifies how semantic alignment using CIDOC CRM, LADO, and OWL-Time can facilitate cross-domain chronological reasoning and strengthen transparent, machine-actionable archaeological research.

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## 247. Conceptualizing Archaeological Data: A LOD-based representation of Göbekli Tepe

*Antonia Lourentzaki (TALOS-AI4SSH, UOC)*

*Maria Papadopoulou (TALOS-AI4SSH, UOC)*

*Christophe Roche (TALOS-AI4SSH, UOC)*

This paper aims to represent the conceptualization and representation of the spatial data and artefacts from the archaeological site of “Göbekli Tepe” in Southeastern Turkey within a FAIR-LOD based framework for the Semantic Web. The resulting knowledge graph, developed in the field of Prehistoric Archaeology, formally defines the archaeological findings and their contextual relationships. Emphasis is placed on the characteristic T-shaped stone pillars, the reliefs they bear, and the sculptures found in the architectural structures. In this context, an ontoterminology - a terminology whose conceptual system is a formal (domain) ontology - has been developed. To achieve this, the ontoTerminology EDitor (TEDI) software (Roche, Papadopoulou, 2019) was used, as it facilitates the construction of knowledge graphs and therefore enabling the standardization of archaeological findings.

Four key aspects of the modelling are discussed: the concept of location and its connection to the artefacts, dating, and the symbolic meaning of motifs. Depending on these main facets, the study examines the position of architectural elements and artefacts of the site, the number of pillars and the distribution and frequency of reliefs across pillars and enclosures, as well as their thematic and symbolic content. By means of SPARQL queries, these questions are investigated to illuminate how such representations intertwine with the social and religious architectural structures of their era.

The information and data used were derived from the published excavation records and articles of the Göbekli Tepe team (Schmidt 2012; Clare 2024), including stratigraphic and artefact information. The ontoterminology was



developed around five core concepts: <Location>, <Material>, <Type of Archaeological Find>, <Symbolic Meaning>, and <Type of Relief>.

The concept <Location> includes definitions, terms, and instances connecting the findings to their provenance through trench and stratigraphic layer associations. Each architectural component and artefact is linked to its find-spot through defined relationships: "isLocatedInLayer" associates objects with geological strata, "isLocatedInTrench" records specific excavation areas, and "isLocatedInEnclosure" or "isLocatedInRectangularBuilding" situates findings within their architectural contexts.

Another key concept, <Type of Archaeological Find>, is divided into three sub-concepts: T-shaped pillars, reliefs, and sculptures. This classification enables relational mapping between reliefs and their corresponding pillars through bidirectional properties (<Pillar> hasRelief <Relief>; <Relief> belongsToPillar <Pillar>) and detailed positional attributes ([LocationInPillar], [hasOrientation], [nearToPillar], [LocationInEnclosure]).

Dating information is managed through TEDI's "begin period" and "end period" functions, allowing temporal assignment within the site's chronological framework, and through editable attributes ([DatedFrom], [DatedTo], [DatedIn]).

<Symbolic Meaning> and its sub-concepts—"Ritual", "Religious Belief" (possible animism or ancestor worship) (Clare, 2024), and <Violence> (notably animal depictions)—introduce a cognitive layer reflecting excavator interpretations.

Göbekli Tepe data are openly accessible and reusable in RDF and HTML formats. RDF allows integration with Protégé, while HTML outputs provide documentation and visualization via URIs. Hosted on the TALOS AI4SSH website (<https://talos-ai4ssh.uoc.gr/>), ontology viewers (the Knowledge Graph Editor and OTV Viewer) ensure interoperability under FAIR principles.

Overall, these tools visualize the ontology structure, enabling scholars and the public to explore and query the dataset, while deriving informed interpretations.

The outcomes of the ontoterminology are visualized through web interfaces. Relations integrating Göbekli Tepe's spatial, architectural, and artefactual data are represented as entities, exportable in RDF and HTML formats.

The RDF export facilitates importing the ontoterminology into other ontology editors, such as "Protégé". In parallel, HTML exports provide accessible documentation for the Term and Proper Name Editors of the ontoterminology, complete with formal and term definitions, bibliographic references, images, and ontological visualizations, for instance, the object collection with its associated images, accessible via URIs.

The TALOS-AI4SSH project website (<https://talos-ai4ssh.uoc.gr/>) hosts specialized viewers rendering ontology tree diagrams, including exports compatible with the Knowledge Graph Editor and the OTV Viewer, made openly accessible. Consequently, the dataset fulfills core FAIR data principles: interoperable, reusable, and openly accessible.

Furthermore, SPARQL queries are constructed to address specific research questions enabling data retrieval, such as counting pillars featuring specific animal reliefs within a designated enclosure or quantifying reliefs by motif or inferred symbolic significance.

These tools provide a clear overview of the ontology structure, visualizing archaeological data within a single integrated platform that allows scholars and the public to explore, question, connect, and draw informed conclusions from the dataset.

This study demonstrates how semantic web and LOD technologies enhance archaeological data documentation and analysis, from stratigraphic to interpretive. From this analysis we infer that ontoterminologies enable the creation of well-documented definitions of terms through hierarchically structured concepts, introducing greater accuracy into research. Ontoterminologies provide well-defined, hierarchical concepts, enhancing precision. These open-access knowledge graphs make documented knowledge available to educators, researchers, students, and non-specialists, allowing them to navigate the data and perform queries.

Version 1.0 of the dataset is openly available through "Zenodo" (<https://talos-ai4ssh.uoc.gr/resources/open-datasets/open-dataset-1-modeling-an->

[illegible]

Fig. 1 The OTV Viewer of the second version of the ontoterminology. Four basic concepts are showcased: <Location>, <Material>, <Type of Archaeological Find>, <Symbolic Meaning>, and <Type of Relief>.

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### 321. FAIRification of Projectile Point Typologies through ArchaMap and Wikidata

*Robert Bischoff (Arizona State University)*

*Daniel Hruschka (Arizona State University)*

*Matthew Peeples (Arizona State University)*

## Introduction

Projectile points are among the most widely used diagnostic artifacts in archaeology, yet their typologies remain fragmented across hundreds of regional, chronological, and researcher-specific classification systems. This fragmentation hinders comparative analyses, reproducibility, and computational integration of archaeological data. To address this, the CatMapper project has used the ArchaMap application and database, an infrastructure designed to create and manage FAIR (Findable, Accessible, Interoperable, Reusable) datasets for archaeological categories and assist in merging datasets. The recent initiative to expand coverage of projectile point types—of which only about twenty are currently represented in Wikidata (Vrandečić, and Krötzsch 2014)(Q2308299 and its subclasses)—illustrates how ArchaMap can

bridge data silos and support the broader Semantic Web ecosystem of archaeology.

### Methods and Materials

ArchaMap integrates heterogeneous typological vocabularies by aligning them through stable identifiers and controlled vocabularies. An ongoing project utilizing undergraduate students and funded by a National Science Foundation grant aggregates projectile point definitions from over thirty published sources, including [projectilepoints.net](http://projectilepoints.net), major regional syntheses, and other publications. Alternate names, spellings, and contextual data (cultures, periods, regions, and administrative districts) are used to capture hierarchical and associative relationships between projectile point types.

Each typological entity in ArchaMap is assigned a persistent identifier (URI), linked to alternate identifiers (AAT, Wikidata QIDs, etc.), and enriched with alternate labels, geographic scope, chronological range, and bibliographic references. The design adheres to FAIR and LOUD (Linked Open Usable Data) principles (Wilkinson et al. 2016; Newbury 2018), ensuring that ArchaMap data can interoperate with external repositories.

### Results

The current ArchaMap dataset contains over 1,500 projectile point types, many of which include multiple alternate names and links to regions, cultures, periods, and modern administrative districts. A pilot integration with Wikidata demonstrates the capacity of ArchaMap to function as both a source of enrichment and a validation framework.

As an example of how ArchaMap can be used to build up Wikidata, the Palmela projectile point type with an ArchaMap identifier of CMID: AM192789 and a Wikidata identifier of Q76308430 were linked using an automatic fuzzy matching algorithm in ArchaMap using the Wikidata name (Palmela point) and the existing ArchaMap label (Palmela points), which was derived from the Getty Art and Architecture Thesaurus. Once the linkage was made, then the Getty Art and Architecture Thesaurus ID was added to Wikidata, as Getty is a recognized entity in Wikidata for storing reference IDs. The

Palmela point entry in Wikidata contains no alternate names or translations, however, the Getty reference does include five alternative names or translations. By creating a linkage in ArchaMap and Wikidata, either resource can be used to identify alternate labels for this projectile point type. Neither Getty nor Wikidata provide any contextual information such as regions, administrative districts, periods, or cultures. In order to include this information, additional datasets would need to be found and added to ArchaMap, a process made simple via ArchaMap's automated tools.

While Wikidata currently includes only a handful of projectile point types, forthcoming linkages with ArchaMap will expand this to a more representative dataset with citation-backed definitions. Moreover, ArchaMap identifiers are being reviewed for official recognition as external identifiers in Wikidata, ensuring bidirectional data exchange. Even without that recognition, the system already allows straightforward alignment because major external thesauri such as the Getty Art & Architecture Thesaurus (AAT) are incorporated into ArchaMap, simplifying their addition to Wikidata entities through shared semantic properties.

### Discussion

This work highlights the importance of FAIR and LOUD data infrastructures for reconciling typological diversity in archaeology. Typological systems—especially those involving projectile points—are simultaneously diagnostic, regional, and interpretive, which makes direct standardization impractical. Instead, semantic interoperability offers a way to model relationships of equivalence, overlap, or uncertainty without collapsing interpretive nuance. By providing persistent identifiers and explicit mappings among sources, ArchaMap transforms previously disconnected typologies into a navigable network of linked archaeological knowledge.

Within the broader context of computational archaeology, this approach demonstrates the practical value of combining Wikibase technology with other datasets utilizing the specially designed tools in ArchaMap for creating translations between datasets. ArchaMap allows archaeologists to visualize

typological relationships, trace provenance across publications, and merge translated datasets to synthesize knowledge.

More broadly, the integration of ArchaMap with Wikidata exemplifies how domain-specific Wikibase instances can complement community-driven knowledge graphs. Rather than duplicating content, ArchaMap structures archaeological expertise into interoperable forms that Wikidata can reuse and extend. This model—combining community curation with expert oversight—provides a template for other archaeological domains, such as ceramics, lithics, or bioarchaeological typologies, that face similar challenges of overlapping classification systems.

### Conclusion

ArchaMap serves as both a research tool and a demonstration of FAIR data implementation for archaeology. Its linkage of over 1,500 projectile point types from North America and beyond establishes the most comprehensive, semantically interoperable typological dataset currently available. As the system expands to integrate with Wikidata, it will not only fill major gaps in open archaeological knowledge graphs but also offer a replicable workflow for FAIRifying typological data across material domains. In doing so, ArchaMap helps to chart the unknown territories of digital archaeology's "data dragons," transforming them into interoperable and reusable knowledge.

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## S3: Methodological and Theoretical Research in Digital Archaeology, Day II

Anja Wutte, University of Cologne, Germany; TU Wien, Austria

Maria Sotomayor Chicote, University of Cologne, Germany

**Location:** Auditorium Maximum

**Session Format:** Standard

|                      |                                                                                                                                                                                                                                                                                                                |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>08:30 – 08:50</b> | 156. From Caves to Codes: A Paradigm Shift in Surveying and Documentation of Rock Art Research in India in a Global Context<br><i>Anindya Sanyal (Banaras Hindu University)</i>                                                                                                                                |
| <b>08:50 – 09:10</b> | 161. Developing a Digital Documentation Model for Seal Impressions Using the RTI Method: A Case Study of the Persepolis Treasury clay sealing<br><i>Negar Farajzadeh (University Of Tehran)</i>                                                                                                                |
| <b>09:10 – 09:30</b> | 61. Digitizing the Sculptural Heritage of the Accademia di Belle Arti di Firenze: Ethics, Methodologies, and Case Studies<br><i>Giulia Vaccari (Accademia di Belle Arti di Firenze, Università di Roma Tor Vergata); Sara Onofrietti (Accademia di Belle Arti di Firenze, Conservatorio "Luigi Cherubini")</i> |
| <b>09:30 – 09:50</b> | 345. Applying the Image Dimension Measuring System for artifact analysis<br><i>Anna Głód (Polish Academy of Sciences); Aldona Kurzawska (Adam Mickiewicz University); Iwona</i>                                                                                                                                |

|                      |                                                                                                                                                                                                                                            |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                      | <i>Sobkowiak-Tabaka (Adam Mickiewicz University); Anita Szczepanek (Polish Academy of Sciences); Marjolein Bosch (Austrian Archaeological Institute, Prehistory Austrian Academy of Sciences)</i>                                          |
| <b>09:50 – 10:10</b> | 136. From fragments to forms: algorithmic modelling and robotic fabrication in ceramic vessel reconstruction<br><i>Jakub Franczuk (Warsaw University of Technology); Sara Boś (SWPS University); Piotr Makowski (University of Warsaw)</i> |
| <b>10:10 – 10:30</b> | 452. The use of 3D point densities for archaeological interpretation<br><i>Joshua Emmitt (Auckland Museum); Rebecca Phillipps (University of Auckland); Stacey Middleton (Auckland Council); Simon Holdaway (University of Auckland)</i>   |
| <b>10:30 – 11:00</b> | Coffee break                                                                                                                                                                                                                               |
| <b>11:00 – 11:20</b> | 261. From Web to CAVE: The CAVE-Kompakkt Viewer for Immersive Archaeological Visualization<br><i>Tom Noack (University of Cologne); Daniel Wickerath (University of Cologne)</i>                                                           |
| <b>11:20 – 11:40</b> | 226. 4D Data capturing and analysis – Why we need standardized reference models for monitoring cultural heritage<br><i>Matthias Kucera (University of Vienna); Parker Van-Valkenburg (Brown University)</i>                                |
| <b>11:40 – 12:00</b> | 112. Integrating social theory with computational methods: The MAPAR QGIS plugin and its multiple applications to study past landscapes                                                                                                    |

*Santiago Tuñas-Corzón (Institute of History, Spanish National Research Council (IH-CSIC))*

**12:00 – 12:20** 200. Mobile GIS and Digital Innovation in Archaeology: The Italian Experience with QField, pyArchInit, and the National Archaeological Geoportal (GNA)  
*Roberto Montagnetti (Università degli Studi dell'Aquila)*

**12:20 – 12:40** 170. Mapping the Potential Location of Roman Wine-making Using Niche Modelling Approaches  
*Roberto Ragno (University of Cambridge); Maria Elena Castiello (University of Lausanne)*

**12:40 – 13:00** 366. Testimony of Stones: A New Method in Ancient Traffic Analysis  
*Murat Dirican (Leiden University); Tuna Kalaycı (Leiden University); Jessica Robkin (University of Central Florida); Martin Steskal (Austrian Academy of Sciences / Austrian Archaeological Institute and Head of Ephesus Archaeological Excavations / Türkiye); Scott Branting (University of Central Florida / Department of Anthropology and Head of Kerkenes Archaeological Excavations / Türkiye)*

**13:00 – 14:00** Lunch break

**14:00 – 14:20** 401. Space time pattern mining: using spatiotemporal analysis for identifying patterns of coin hoarding across the Imperial Roman Empire  
*Christina Zymari (Independent)*

**14:20 – 14:40** 250. Trait-Based Multivariate and Network Analysis of Sasanian Ceramic Technologies: From Sherd Patterns to Regional Systems in Southern Iran  
*Sona Naderi (University of Tehran); Zohreh Zehbari (Philipps-Universität, Marburg)*

**14:40 – 15:00** 302. Beyond Application: Rethinking Spatial Interaction Modelling in Mycenaean Archaeology  
*Areti Michalopoulou (University of Cologne)*

**15:00 – 15:20** 310. Playing With Fire? – Fire Simulation as a Tool for Spatial Analysis of Open-Air Sites  
*Rebecca Gnau (University of Cologne)*

**15:20 – 15:40** 315. ArchaeoSky: A Quantitative Platform for the Analysis of Astronomical Alignments in the Roman World  
*Vasileia Lianou (West university of timisoara)*

**15:40 – 16:00** 379. Modeling the Deep Roots of Resilience – A Computational Framework for Organizational Adaptation in Hominin Evolution  
*Ericson Hölzchen (Trier University); Veronika Kurchyna (German Research Center for Artificial Intelligence (DFKI), Trier University); Ana Mateos (Centro Nacional de Investigación sobre la Evolución Humana (CENIEH)); Jesús Rodríguez (Centro Nacional de Investigación sobre la Evolución Humana (CENIEH)); Christine Hertler (ROCEEH Research Center, Senckenberg Research Institute and Heidelberg Academy of Sciences and Humanities); Jan Ole Berndt (German Research Center for Artificial Intelligence (DFKI) and Trier University); Ingo J. Timm (Trier University and*



## 61. Digitizing the Sculptural Heritage of the Accademia di Belle Arti di Firenze: Ethics, Methodologies, and Case Studies

*Giulia Vaccari (Accademia di Belle Arti di Firenze, Università di Roma Tor Vergata)*

*Sara Onofrietti (Accademia di Belle Arti di Firenze, Conservatorio "Luigi Cherubini")*

In a cultural landscape increasingly shaped by privatization and commercial logics, artistic heritage calls for new strategies capable of reaffirming its civic and social function. This research focuses on the historical and digital re-evaluation of the sculptural heritage of the Accademia di Belle Arti di Firenze, with particular emphasis on its extensive collection of plaster casts.

Founded in 1784 by Grand Duke Pietro Leopoldo, the Accademia di Belle Arti di Firenze was established through a separation from the earlier Accademia del Disegno – the first art academy in the world, founded by Giorgio Vasari in 1563. From its earliest inventory, compiled in 1785, the Academy already possessed a remarkably rich collection comprising approximately four hundred objects of varying scale and typology. This corpus included a significant number of statues, plaster casts, and gypsum models, alongside a wide range of other artistic artefacts, reflecting the central role of sculptural reproduction in academic training and artistic transmission during the late eighteenth and nineteenth centuries.

Traditionally conceived as didactic tools and rarely accessible to the public, these works are now at the center of a long-term project that combines art-historical research, cataloguing, and digital technologies to restore their dignity and relevance.

The project operates within a national context in which cultural assets are frequently subjected to managerial practices that contradict the principles of heritage care and accessibility. Within this framework, the AMABAFi (Archivio Multimediale dell'Accademia di Belle Arti di Firenze) aims to document, preserve, and make accessible - both physically and virtually – this unique collection, which since its foundation it has grown through donations, exchanges, and musealisation processes into a corpus comparable in scale to that of a museum.

Among the first digitization experiments are the nineteenth-century plaster casts of Michelangelo's Lia and Rachele, moulded by Leopoldo Malpieri, which allow full visual and analytical access to sculptures otherwise partially obscured in their original architectural settings. More recently, the research has involved the restoration and 3D digitization of the historic cast of Ghiberti's Porta del Paradiso ("Gate of Paradise"), made in 1772 by Vincenzo Ciampi - presumably the earliest cast ever made from the original. Conducted in 2025 under the PNRR EAR Project (WP4), the intervention combined surface conservation with high-precision photogrammetry. Due to the cast's monumental dimensions, a hybrid protocol was developed, integrating topographic and close-range photogrammetry to produce a detailed, metrically consistent 3D model. This workflow has since been defined as a replicable standard for similar academic and conservation contexts.

Digitization, in this sense, extends beyond technical documentation: it functions as a cultural and ethical act, reactivating plaster casts as mediators of knowledge. Digital models contribute to preservation and diagnostics, reduce physical handling, and support virtual exhibitions, interactive applications, and hybrid learning tools.

The project therefore proposes a hybrid model of heritage regeneration, merging critical museology, digital humanities, and curatorial practice. Through AMABAFi, the Accademia becomes a civic laboratory where

historical artefacts are reconnected with contemporary communities, reinterpreting plaster casts as dynamic cultural interfaces that foster memory, participation, and collective belonging.

All activities are conducted with formal institutional authorization and exclusively for non-commercial, scientific, and educational purposes, in full compliance with the Codice dei Beni Culturali e del Paesaggio (Legislative Decree no. 42/2004). In particular, the digitization project concerning the two plaster replicas of Michelangelo's sculptures was carried out in compliance with national guidelines and European technical and operational protocols. Appropriate equipment, methodologies, and workflows were adopted, and the digitization process was structured in relation to the resources, spaces, and technical infrastructure available within the institutional context of the Accademia di Belle Arti di Firenze. The following guidelines and reference documents were adopted as methodological frameworks:

- Linee guida sulla digitalizzazione del patrimonio culturale, Istituto Centrale per la Digitalizzazione del Patrimonio Culturale (2022);
- Basic Principles and Tips for 3D Digitisation of Tangible Cultural Heritage for Cultural Heritage Professionals and Institutions, DCHE Expert Group (2020);
- The London Charter for the Computer-Based Visualisation of Cultural Heritage, H. Denard (2009).

#### Preliminary and Expected Outcomes

The preliminary outcomes of the research confirm the potential of digital technologies as both tools of preservation and agents of cultural regeneration. The digitization of the Accademia's heritage has already produced a corpus of high-resolution 2D and 3D models that serve as instruments for documentation, conservation monitoring, and comparative art-historical analysis. These models form the basis of a new multimedia archive-interoperable, open-access, and conceived as a dynamic platform for scholars, students, and the wider public. Beyond its technical scope, this archive redefines the principles of museological accessibility by enabling the circulation of knowledge traditionally confined within academic boundaries.

From a methodological and pedagogical perspective, the project contributes to the development of a standardized workflow for the digitization of sculptural heritage, one that can be replicated and adapted by other institutions. This framework integrates art-historical expertise, conservation science, and digital humanities, promoting a multidisciplinary learning environment within the Academy itself. Students are directly involved during the process - cataloguing, documentation, and communication - thus fostering the transfer of digital and curatorial competencies essential for the contemporary cultural sector.

In social and cultural terms, the project expands public access to collections that were historically restricted to internal use, transforming them into shared cultural resources. Through online platforms, virtual exhibitions, and interactive tools, the Accademia's heritage becomes accessible to diverse audiences, stimulating new forms of participation and civic engagement. In this sense, the research advocates for an ethically grounded model of digitization-one that resists the commodification of culture exemplified by NFTs or branding logics, and instead restores the cultural Institution's role as a space of education, inclusion, and collective memory.

Finally, on the art-historical level, the project repositions plaster casts as autonomous cultural artefacts rather than mere pedagogical aids. By combining archival research with digital analysis, it opens new interpretative and comparative perspectives on materials, techniques, and artistic transmission across centuries. The expected result is not only a revitalization of a neglected heritage but also a broader reflection on how digital technologies can sustain both the preservation and the democratic accessibility of art.

## 112. Integrating social theory with computational methods: The MAPAR QGIS plugin and its multiple applications to study past landscapes

*Santiago Tuñas-Corzón (Institute of History, Spanish National Research Council (IH-CSIC))*

Nowadays, more and more archaeologists are able to go beyond a simple “push-button” use of ready-made computational tools to actually create their own to produce data that better suits their needs. This is positive and necessary for improving the discipline. However, there is something really concerning about it, and this is the growing tendency to amass huge amounts of data, using highly sophisticated methods, that in the end are very rarely interpreted to answer specific historical questions.

The aim of this paper is to show that it is possible (and necessary) to integrate social theory with computational methods. In particular, a recently developed QGIS plugin will be presented, and its applications to analyse settlement patterns in past landscapes discussed. The MAPAR plugin (Mapping Agricultural Potential in Archaeological Research) creates, classifies, and combines at least four layers (elevation, slope, soil erosion, and wetness) to produce a map of potential agricultural productivity suitable for archaeological spatial analysis. Designed with flexibility, it can be adapted to different agrarian societies, allowing users to define as many land categories as needed. The tool also includes a machine learning option to detect specific landscape features: either zones unsuitable for cultivation (rocky soils, water bodies, beaches) or modern artificial elements (urban areas, open-cast mines, quarries) which are inappropriate to model pre-modern landscapes. Additional layers, such as temperature or geology, can also be included by the user.

The maps generated with MAPAR aim to capture the structural properties of the land, following FAO land evaluation guidelines from the 1970s. Perhaps more important is the fact that it also allows users to experiment with different parameters to reflect their prior assumptions about the level of technical and productive development of past societies. This methodological approach should not be considered an end in itself but a mechanism to reach a higher goal. The objective is not the realistic reconstruction of past environments but the use of these maps as proxies to test hypotheses about the spatial structure —and the social organisation behind it— of the societies studied

(Currás 2014). The extensive spatial analysis of Iron Age hillforts in north-western Iberia offers an excellent case study to illustrate this.

The first millennium BC in NW Iberia saw the emergence, spread and transformation of a unique type of settlement, always enclosed and fortified. These hillforts, known as castros, are characterised by their small size and represent the only form of territorial organisation throughout the entire period. This explains why no open Iron Age site has ever been found; it was not due to lack of research but as a result of a deliberate socio-political construction by Iron Age communities.

How to characterise the social structure of the castro landscapes has been a major concern for the specialists on Iron Age NW Iberia over the last few decades. While some consider that there was a tendency towards social inequality throughout the period, with a turning point in the 4th century BC (González-Ruibal 2006), others propose an egalitarian interpretation, based on Durkheim's idea of segmentary societies, valid until the Roman influence in the region (Currás and Sastre 2020). The first group of researchers usually rely, either implicitly or explicitly, on circumscription theory to explain social change and the emergence of hierarchy. According to this view, a presumed intensification of production would lead to demographic growth and, consequently, to a higher social pressure on the environment. This situation would derive first in competition for resources, then in conflict, and finally in the emergence of warrior elites. On the other hand, to those who advocate for a model of segmentary societies, the absence of circumscription becomes a necessary condition to sustain an egalitarian interpretation.

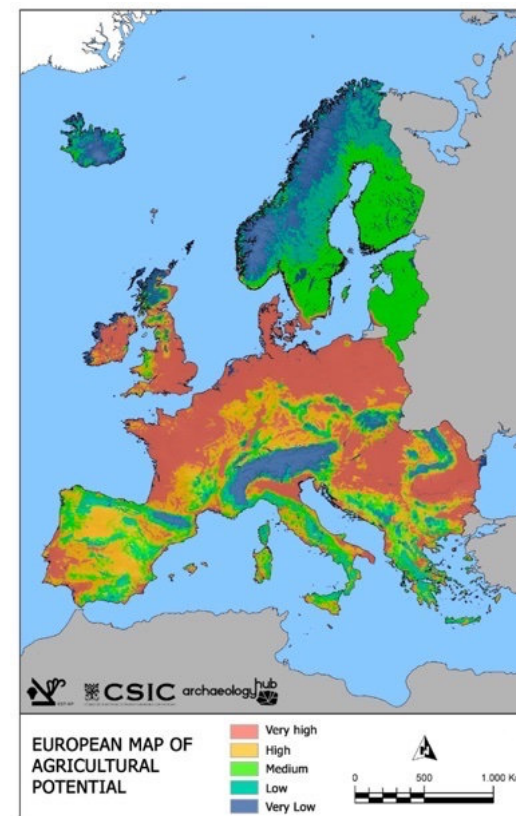
In order to test circumscription theory in Iron Age Galicia, a sophisticated, albeit computationally demanding, form of site catchment analysis was implemented. Using the MAPAR tool to estimate the resources, and settlement size as a demographic proxy, this procedure consisted on expanding the catchments of all sites until they reached the necessary amount of land required to satisfy their population's dietary needs. This was done simultaneously for every site, ensuring that in case of contact and overlapping between

catchments, these kept an exclusive territory separated by cost-based borders.

The results show that all castros had sufficient resources in their surroundings to support their estimated populations. This is true even under the extreme conditions (demographic and productive) introduced into the model. Just as MAPAR does not aim the positive reconstruction of past environments, this site catchment analysis does not intend a realistic estimation of territorial divisions but rather to test a hypothesis under an unreal, worst-case scenario. If all castros had enough land nearby under these extreme conditions, they certainly did so during the Iron Age.

Other possible MAPAR applications include locational modelling or assessing the relationship between accessibility to agrarian resources and settlement size. The former was approached with a point process model, which confirmed the key role of agricultural productivity, topographic prominence, and spatial inhibition in the distribution of castros. The latter, by contrast, showed that large sites had no better access to resources than smaller ones.

The MAPAR plugin offers multiple possibilities to test hypotheses emerging from social theory. Site catchment analysis, point process modelling, and the assessment of settlement hierarchy are among its most useful applications. But these are not the only ones. The key lies in designing the methodology around a specific historical question, rather than the other way round. Focusing exclusively on a technique without a theoretical basis will simply result in data devoid of historical value. This growing imbalance favouring method over theory is a major problem in archaeological science today. Computational archaeology certainly has the potential to address historical questions that could not otherwise be answered, but if “it’s all about people”, as the official motto of CAA 2026 says, this can only be achieved by integrating social theory with computational methods.



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González-Ruibal, A. 2006. Galaicos. Poder y comunidad en el noroeste de la Península Ibérica (1200 a.C. – 50 d.C.). Brigantium, 19.

### 136. From fragments to forms: algorithmic modelling and robotic fabrication in ceramic vessel reconstruction

*Jakub Franczuk (Warsaw University of Technology)*

*Sara Boś (SWPS University)*

*Piotr Makowski (University of Warsaw)*

The reconstruction of fragmentary ceramic archaeological finds is a fundamental but still unresolved challenge in digital archaeology. Traditional manual reconstruction, although methodologically mature, remains subjective, time-consuming and limited by the researcher's interpretative biases. Computer-aided feature-based reassembly and matching have improved efficiency, but these techniques still yield single, deterministic results that obscure the inherent uncertainty of archaeological interpretation. This article presents an ongoing research project aimed at investigating algorithmic methods for reconstructing ancient ceramic vessels by combining parametric modelling, probabilistic form generation, robotic production and interactive visualisation as complementary elements of a repeatable and transparent process.

The study focuses on ceramic fragments excavated from four archaeological sites in Jordan — Tell Abu Sarbut, Beit Ras, Gharandal, and Umm Qais. These assemblages include a variety of typologies, such as transport amphorae, bowls, and fineware vessels, whose incomplete state makes traditional extrapolation unreliable. Instead of attempting to define a single definitive geometry, our approach produces a range of plausible reconstructions derived from the measurable properties of each fragment. The basis for developing the definitions was photogrammetric models of real elements. The

algorithmic process, developed in Rhino + Grasshopper, uses parametric rules to infer the shape of the vessel and the variation in thickness based on partial profiles. The procedural model allows for dynamic adjustment of these parameters to generate multiple hypotheses, each representing a different typological interpretation consistent with the same archaeological evidence.

To make these variations accessible and interpretable, the models are published through ShapeDiver, an online parametric viewer that enables interactive exploration of reconstruction alternatives. Users, whether archaeologists, students, or the general public, can manipulate input parameters and visualise how minor assumptions about curvature or rim orientation alter the final shape. This interactive environment transforms reconstruction from a static representation into a transparent process of negotiation, explicitly revealing the degree of uncertainty and subjectivity that underlie each virtual artefact.

The geometric outputs are also connected to the KUKA prc for robotic clay printing. By printing computer-generated clay moulds, the project tests the structural feasibility and realism of each digital hypothesis. The robotic fabrication phase serves both validation and exploration. Printed prototypes reveal geometric stresses, weight-induced deformations, and material deformations, which provide the basis for further refinement of the algorithms. This coupling of computational logic and tangible materiality situates algorithmic reconstruction within the domain of experimental archaeology.

Methodologically, the project positions algorithmic design not as a tool for producing the “correct” reconstruction but as a medium for exploring and communicating the ambiguity of interpretation. The process clearly separates measured limitations (resulting from geometry, curvature and thickness) from inferred constraints (symmetry, proportions, typological analogies). Each reconstruction variant can therefore be traced, compared and reproduced, ensuring a transparent record of interpretative decisions.. The

visualisation interface allows these decisions to be shared and questioned, promoting collaborative interpretation and accountability in digital heritage research.

This approach challenges the binary distinction between actual and hypothetical reconstructions, proposing instead a parametric space of possibilities — a spectrum of plausible shapes generated within archaeologically valid limits. By encoding epistemic openness directly into the computational model and by exposing it through interactive visualisation, the project redefines reconstruction as an open-ended reasoning process rather than a final product. Such an approach resonates with the epistemology of negotiated reconstruction.

Preliminary results show that algorithmic procedures can capture vessel geometry families consistent with archaeological context and typology, while robot-made prototypes confirm their physical consistency. Future development focuses on incorporating decorative patterns and surface textures to extend morphological inference. The integration of interactive visualisation and robotic fabrication opens new pathways for communicating the plurality of archaeological interpretation, allowing both experts and non-experts to engage critically with multiple, coexisting variants.

In a broader perspective, this research demonstrates how computational design and robotic processes can serve as instruments of interpretation, rather than automation, in archaeological reconstruction. Algorithmic reconstruction shifts the focus from reconstructing a lost object to reconstructing the reasoning process itself — a step toward more reflexive and participatory digital archaeology.

## 156. From Caves to Codes: A Paradigm Shift in Surveying and Documentation of Rock Art Research in India in a Global Context

*Anindya Sanyal (Banaras Hindu University)*

Palaeo art has long served as a medium of communication for ancient Homo societies illustrating their multidimensional interactions with the environment and surroundings. Interpretation of these art forms is crucial for understanding the ancient Homo societies and its individual components, which played various roles in the continuation of these societies, driving the evolution process forward, especially in a country like India which houses different varieties of rock art spread over different terrain and environmental settings. Rock art, being a perishable archeological commodity, is highly susceptible to destruction due to natural and artificial factors, thus, surveying and documentation becomes the most important tool to study and interpret rock art. Due to the higher decay susceptibility, inclusion of various theoretical, technological, geospatial, and scientific tools becomes an essential component in survey and documentation. These tools not only help in accurate and mobile recording of data, but also ensure digital repositories that can be used to attract larger audiences without physically disturbing the site or its context.

Surveying and documentation have always been pivotal in archaeological research since its inception. Meticulous and detailed survey and micro-documentation enables to generate maximum raw data which serves as a warehouse for future research, analysis, and interpretation. Initially, the entire recording process was purely observational and was directly noted or drawn on paper. First ever recording of rock art in India was done by ACL Carlyle in 1867-68. The major issue with observational recording and documentation was the lack of accuracy of the data collected. With technological advancement, cameras and video recorders, mics became essential in the field surveys and documentation. Over time, these practices have undergone a



complete makeover, moving from purely observational, paper-based documentation to technologically aided digital and analog methods. While the global Rock Art community was integrating different technical methodologies to survey and document sites by using high end cameras, video recorders, GPS, ethnographic interviews, etc., India witnessed a significant boost in theoretical and technical documentation of rock art in the late 20th century, especially after the successful archaeological research in Bhimbetka, prompting institutions like the Indira Gandhi National Centre for the Arts (IGNCA), Rock Art Society of India (RASI), and the Archaeological Survey of India (ASI) employing digital photography and GPS mapping (Blinkhorn 2012, Kumar 2023).

In the last decade or so, a new wave of tech integrated methodology revolutionised Rock Art research in India. The new wave of innovation of technological tools, softwares, and scientific tools such as involving geospatial tools like GPS and LiDAR to understand site location and terrain, and using geospatial data repositories such as BHUKOSH to understand the landscape and topography of the area, and interpret various aspects of location, landscape, and site selection processes. Advanced analytical tools such as portable Raman spectroscopy and XRF as part of the documentation toolkit, empower researchers to collect data for pigment content and its analysis generating multi-dimensional interpretations.

The previous documentation sheets were mostly fragmented and often subjective. The documentation sheets often lacked integration technology and software while documenting data during surveys and field visits while the fragmented nature of the previously used sheet ensured that there was a lack of a single structured questionnaire to collect data. To resolve this issue, our team has introduced SHRI (Structured Holistic Rock-art Inventory) - a robust and detailed documentation sheet that enhances metadata creation and standardization for rock art recording, enabling more precise and comparative analysis across sites. The idea is to create a rapid recording form with questions and listed answers ensuring a quick on-field recording. The sheet is divided in different sections dedicated to the different proxies available at a Rock Art site, containing a set of previously designed questions - like

archaeological, lithological, environmental, ethnographical, etc. This allows micro-documentation of every little interaction of the site with its surroundings which lacked previous rock art documentation models. The documentation sheet has sections for recording political and geographical location, in addition to topographical and lithological data. The recorded data can be integrated with the digital repositories to analyse different factors regarding site selection and habitation processes. All the data can be used to create maps, illustrations or digital virtual repositories based on political boundaries, topographical, or terrain. A separate section covers environmental data in which the present condition of the site and its environmental interactions like the available flora-fauna can be recorded, in addition, integration of tools like Temperature and Humidity Data Logger could further expand the scope of research by integrating data of temperature and humidity fluctuations. Similarly, a dedicated section logs data about the Rock Art Shelter or Cave - its geo-location, cardinal location, dimensions. Details about type of rock art, surface, technique, colouration, various panels, superimposition, etc. can be collected, while the micro-documentation table for every panel ensures comprehensive documentation of all available images. All this data can be collected through various technical and scientific tools like distometer, GPS, p-XRF, etc., and later processed to create different data repositories for research on human cognition and evolution, creating virtual rock art sites, etc. Ethnography is an integral part of the sheet, incorporating all the data about the societal structure, religio-cultural practices, tangible and intangible art forms, etc.

SHRI documentation sheet ensures an in-depth and rapid recording at a rock art site. Integration of various surveying and documentation methodologies, especially those of archeology, anthropology, geology, and environmental science while integrating technical tools to leverage accuracy and speed, was among the primary motives, to be able to generate data that can be used to generate holistic and trans-disciplinary interpretations about human cognition and evolution. SHRI documentation sheet offers a more inclusive, interdisciplinary, and holistic approach to documentation and interpretation of

rock art, integrating archaeology with anthropology, semiotics, art history, and digital technologies.

**Keywords:** Rock Art, Micro-Documentation, Metadata, SHRI, BHUKOSH

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## 161. Developing a Digital Documentation Model for Seal Impressions Using the RTI Method: A Case Study of the Persepolis Treasury clay sealing

*Negar Farajzadeh (University of Tehran)*

### 1. Introduction

Seals and seal impressions are among the most important cultural artifacts, providing archaeologists and researchers in related fields with extensive information about the political, administrative, cultural, social, and economic structures of past societies. For this reason, sigillography—the study of seals and seal impressions—has gained a special place in today's scholarly world.

Moreover, the documentation of such cultural materials represents one of the most significant and challenging aspects of archaeology. This study not only introduces the Reflectance Transformation Imaging (RTI) method, one of the most effective tools in digital documentation for this field, but also tests its efficiency and advantages by applying it to a collection of clay sealings from the Persepolis Treasury in Iran, one of the most important and valuable archives of the Achaemenid period.

Demonstrating the impact of accurate documentation, recording, and description of cultural materials on the validity of archaeological and interdisciplinary analyses constitutes one of the main goals and points of importance in this research.

### 2. Materials and Methods

The research was conducted in two parts: library studies and fieldwork.

A) Library Studies: Review and analysis of scientific sources concerning the importance of documentation in archaeology, evaluation of various digital imaging methods, and selection of RTI as the main tool of study.

B) Fieldwork: Implementation of the RTI imaging process on a sample of clay sealings from the Persepolis Treasury, data analysis and thematic classification, and finally the preliminary design of an online digital database for archiving and sharing the documented data.

The RTI method, by capturing multiple images of an object under different lighting angles, enables interactive viewing and reconstruction of surface details invisible to the naked eye. This feature has made it a key non-contact method for documenting fragile artifacts.

### 3. Results and Discussion

The impact of accurate description, recording, and documentation of cultural data on archaeological and related research analyses is one of the key points of significance in this study.

Documentation of archaeological evidence worldwide requires new and innovative spatial experiences; therefore, existing methods must be re-evaluated and updated. This demands a tangible understanding and emphasis on the direct effect of documentation quality on the scientific analyses derived from it.

The RTI method, as one of the most advanced and efficient tools in digital documentation, enables researchers to extract highly precise information. Other advantages include increased speed and time-saving in documenting seal impressions and, more broadly, the written information on clay tablets. Equally essential as accurate documentation is the ease of dissemination and accessibility of archaeological evidence for researchers across different disciplines. This requires the establishment of digital archives and online databases. Such databases not only allow scholars worldwide to study archaeological materials but also help democratize access to cultural data, reducing the monopolization of information by specific countries, museums, or individuals.

A key objective of database design and implementation in archaeology is data reuse, which plays an essential role in:

- a) allowing archaeologists to revisit and reinterpret earlier findings as their experience grows;
- b) sharing field research results among archaeologists;
- c) facilitating interdisciplinary research by sharing archaeological data and findings

The RTI application on the Persepolis clay sealings revealed several transformative outcomes:

#### 1. Enhanced Accuracy in Reading and Representing Motifs

RTI exposed details such as folds in garments, facial lines, surface damages, and stylistic differences in engraving—features often invisible in traditional photography or manual drawing. For instance, detailed analysis of human figures and clothing on sealing no. 46-1921 provided new insights into military dress and social hierarchies during the Achaemenid period.



*Figure 1: representing seal impression using regular photography*



*Figure 2: representing seal impression using RTI*

#### 2. Improved Classification and Comparative Analysis of Seals

RTI enabled recognition of subtle differences between similar artifacts. Comparing different sealings revealed minor variations suggesting multiple versions of a single seal—a finding significant for understanding the administrative and production systems of the Achaemenid era.

3. Creating a Digital Platform for Future Research: RTI images can be archived, reproduced, and reanalyzed long-term, serving as the foundation for digital databases.

4. Preservation and Interdisciplinary Applications: As a non-contact and precise tool, RTI allows for monitoring surface changes, identifying damages, guiding restorations, and even detecting forgeries.

5. Dynamic and Interactive Visualization: Unlike traditional static methods, RTI provides a dynamic viewing experience, allowing researchers to alter the lighting angle and examine each surface feature in real time.

6. Building a Digital Database: In the next step, RTI-derived data were stored in an online database. This digital archive not only ensures open and fast access for scholars worldwide but also provides a platform for large-scale analyses, comparative studies, and interdisciplinary projects. Initiatives like CDLI

(Cuneiform Digital Library Initiative) have demonstrated that open access to data enhances scientific collaboration, reduces human error, and establishes global standards in digital archaeology.

## 5. Conclusion

The use of RTI technology in documenting seal impressions on clay tablets has created a fundamental transformation in documentation and analysis methods in archaeology. By increasing accuracy, facilitating data sharing, and enabling data reproduction, RTI provides an ideal platform for comparative, conservation, and interdisciplinary studies.

In fact, updating diagnostic-descriptive tools (such as RTI software) can significantly shift the trajectory of archaeological research. Ultimately, integrating RTI documentation with online databases represents a crucial step toward achieving an “open, precise, and sustainable digital archaeology.”

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## 170. Mapping the Potential Location of Roman Winemaking Using Niche Modelling Approaches

*Roberto Ragno (University of Cambridge)*

*Maria Elena Castiello (University of Lausanne)*

The significance of wine production in the Roman period has long been recognised as a key element of the imperial economy. However, the extant research on this commodity has been limited in scope, either geographically or in terms of its focus on the distribution of amphoras, which are more indicative of trade patterns than production.

This paper uses machine learning approaches to attempt to reconstruct the spatial extent of wine production in continental Italy during the late Roman Republic and Late Imperial periods (1st c. BCE – 5th c. CE ca.). Our dataset draws on a comprehensive unpublished summary of over 90 sites with archaeological evidence of wine production, excluding those with uncertain classifications where features could relate to either wine or olive oil production. Most of these features are located in Roman villas — notoriously large-scale wine production estates — where Italian archaeological research has focused large excavation efforts over the last few decades. Amphora distributions were intentionally excluded to focus on production rather than consumption or trade networks.

In addition to sites where wine production is evidenced by archaeological features (vats, presses, treading floors, cellar areas, etc.), we integrated 35 sites with archaeobotanical evidence for the presence of *Vitis vinifera* where contexts have been stratigraphically dated to the same chronological framework (Ragno 2025).

While previous works have explored wine production patterns through spatial analysis and, more recently, agent-based models (cf. Dodd and van Limbergen 2024), the role of environmental and climatic factors in shaping the spatial distribution of viticulture has not yet been systematically quantified through niche modelling approaches. We address this gap by applying Niche Modelling approaches using Maximum Entropy (MaxEnt) and Random Forest

(following Castiello et al. 2025) to quantify the influence of environmental and climatic variables (rainfall, temperature, distance to rivers, elevation, etc.) as well as the distance from main Roman infrastructures (cities and roads) on Roman viticulture. This is achieved by triangulating production system mapping and archaeological/archaeobotanical data. This method allows us to predict potential locations of grape presence, absence, and pseudo-absence across the landscape, thereby providing additional clarity on the environmental and climatic parameters that shaped Roman wine production. This research broadens the focus beyond infrastructural remains, highlighting the potential of combining niche modelling and advanced computational tools to model the scale of winemaking production systems in continental Italy. This integrated approach not only enhances our understanding of these processes but also offers a scalable framework for exploring other complex human–environment and climate interactions during the Roman and Late Roman period in the archaeological/archaeobotanical record.

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## 200. Mobile GIS and Digital Innovation in Archaeology: The Italian Experience with QField, pyArchInit, and the National Archaeological Geoportal (GNA)

*Roberto Montagnetti (Università degli Studi dell'Aquila)*

This paper examines the dual impact of Mobile GIS on archaeological practice, focusing on two distinct yet complementary areas of application: the management of excavation data and the production of territorial archaeological data for the Italian Geoportal for Archaeology (GNA), the Italian web platform for the publication and consultation of archaeological information in Italy.

In the first area, the combined use of QField and pyArchInit allows the entire excavation GIS platform to be transferred onto a mobile device, enabling the direct recording of US/USM and, more broadly, all excavation-related documentation, while continuously updating the central database. This approach eliminates the need for expensive and fragile paper forms, drastically reduces data-entry time, and allows constant supervision of field's team operations. The integration of survey, documentation, and spatial analysis turns the excavation site into a truly digital environment, where time and resources are optimized and data quality control is immediate.

In the second area, the use of the ICA Template—a QGIS-based project built on a GeoPackage database distributed by the ICA (Istituto Centrale per l'Archeologia) for the recording of archaeological data from excavations, preventive archaeology, and landscape research—directly within QField has made it possible to extend the benefits of Mobile GIS to territorial activities. This includes preventive archaeology surveys and archaeological mapping projects, such as the creation of Archaeological Desk Based Assessment and Archaeological Evaluation used in spatial planning and heritage management. Recording data according to the standards and controlled vocabularies of the GNA allows the production, in real time, of interoperable and standardized information consistent with the workflows defined by the national guidelines (DPCM, 14 February 2022).

The integration of these open-source tools represents a substantial methodological improvement for archaeologists: greater autonomy in data management, reduced processing time, enhanced data quality, and full compliance with national documentation standards. In this sense, Mobile GIS should be seen not only as a technological upgrade, but as a catalyst for efficiency, transparency, and the open sharing of archaeological data.

## 226. 4D Data capturing and analysis – Why we need standardized reference models for monitoring cultural heritage

*Matthias Kucera (University of Vienna)*

*Parker VanValkenburgh (Brown University)*

### Abstract

Although cultural Heritage had always been under risk, possible threats are currently multiplied due to environmental changes and massive human influence. In addition, destructive and endangering phenomena get observable more clearly based on technical and methodological developments. General visibility is also increased by new media and its accessibility to a wide public. Accurate 3D data recording enables the complete documentation of the status of a monument or landscape at a specific moment in time (Adamopoulos and Rinaudo 2021). Repeated recording allows the monitoring of spatio-temporal changes of an entity, which can be the basis for further analysis (Lercari 2019). This gets even more critical, when not only the monument itself is under threat, but also visitors endangered by possible collapses, earth slides or rockfall. In 2022 parts of the fortification wall of the archaeological site Kuelap in the region of Chachapoyas/Peru collapsed and caused a mass movement of more than 450 m<sup>3</sup> (Ghezzi et al. 2024). Only by chance was the place closed at that time. To analyze the genesis of the collapse and to work on strategies for predicting future events the whole site was recorded in 3D and compared to legacy datasets preceding the collapse. During the survey and processing of the different datasets several challenges

occurred, which highlighted the demand for well-defined and standardized workflows to guarantee a valid reference model to compare all datasets reproducible and traceable.

### Context

Recent years have seen a massive increase in the application of different 3D recording techniques and their combination. Whereas 3D Laserscanning (LS) became an important tool 2 decades ago, novel approaches in photogrammetry initiated by digital photography resulted in Image based modelling (IBM) the following years. Nowadays these different techniques provide a portfolio to cover various scenarios and demands efficiently. Still, one of the most crucial issues is correct georeferencing of the data. For IBM-based data this also safeguards correct scaling. Consequently, each project must be accompanied by a geodetic survey relying on GNSS technologies, total stations or both defining absolute spatial accuracy of the data. As IBM and LS can be carried out ground based (terrestrial) and/or airborne, a multifaceted set of data must be treated and unified. During processing aligned point clouds can be triangulated making various 3D formats accessible for further analysis and display.

It must be highlighted that it makes no sense to define a minimum level of accuracy (and precision) in general. Every scenario is unique and demands specific approaches resulting in various degrees of accuracy. Nevertheless, the knowledge of the accuracy given is crucial for comparability and reproducibility. When monitoring a site or landscape it is demanding to guarantee consistency of the different datasets, especially when legacy data sets must be considered. A main question, which must be asked, is how the recorded geometry reflects real geometry. Recent developments in processing - especially LS data sets - revealed the advantages of geometry-based alignment of point clouds. These aspects are extremely important when analyzing changes in time.

Argument – standard reference model



When comparing 3D datasets of the same entity recorded at different times, several challenges must be faced. Ideally both surveys have been carried out under the same conditions and survey strategies. In addition, georeferencing must be as accurate as possible. When working on the data recorded at Kuelap in Peru it became obvious that these demanding premises must be argued. Furthermore, these aspects seem to be of major concern for comparable monitoring projects. Luckily the collapsed part of the fortification had been recorded with TLS already in 2019 with the same type of Laser scanner (Riegl LMS VZ-series) and rescanned after the disaster in 2022 by the same team. Besides the TLS surveys, additional data derived from ground-based IBM, airborne IBM, and Unmanned LS (ULS) was available. Whereas the TLS surveys have been accompanied by geodetic surveys, all other surveys are of varying georeferencing quality. Alignment was planned – and carried out – in deriving respective control points (and surfaces) from the TLS data. It turned out that changes of geometry can be only monitored relative to one moment in time, i.e. the model of Kuleap derived from the complete TLS survey from 2022. This model must be assumed to be most comparable to the real geometry in 2022. For this purpose, a professional geodetic survey had been conducted – in a situation where also the geodetically determined ground points cannot be expected to be stable for local geological reasons. Besides the cause of the collapse, prediction of future rockfall is crucial to increase safety on site. Minimal changes within the range of millimeters must be controllable, which demands the highest level of accuracy (and precision). Thus, the TLS model of 2022 must provide highest intrinsic accuracy, stabilized by the geodetic survey and the statistical and mathematical analysis of the alignment of all single scan positions necessary for the complete coverage of the site. The TLS based digital twin from 2022 can be defined as a standard reference model, to which all other datasets can be compared and aligned based on geometrical approaches.

## Discussion

When starting the monitoring project in Kuelap the team was confronted with different challenging aspects: the specific environmental and geological

situation, the topography (the site is located at 3000m ASL along a cliff top), dense vegetation, the application of different 3d recording techniques and the need of highest absolute accuracy to monitor minimal spatial changes. The introduction of a standard reference model and the resulting discussion of its value and purpose is a blueprint for numerous 3D surveys in cultural heritage and archaeology not only in remote areas. It enables quantitative spatio-temporal analysis at various levels of scale and accuracy. These levels depend on specific demands. Their documentation safeguards the traceability and reproducibility of results and fosters comparability with other datasets. In this respect the standard reference model derived from the TLS dataset and a geodetic survey is the geometrical backbone for further analysis.

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## 250. Trait-Based Multivariate and Network Analysis of Sasanian Ceramic Technologies: From Sherd Patterns to Regional Systems in Southern Iran

*Sona Naderi (University of Tehran)*

*Zohreh Zehbari (Philipps-Universität, Marburg)*

### Introduction

This paper presents a multiscale analysis of ceramic technology in the Sasanian-period landscapes of Dashtestan (Bushehr Province, southern Iran), focusing on how technological choices were organized, transmitted, and varied across archaeological contexts. The study addresses a central research question: to what extent do macroscopic ceramic traits reflect coherent production systems, technological standardization, or fluid networks of craft transmission?

Sasanian ceramics are traditionally categorized into typological classes—based on morphology and stylistic features. However, typological labels often mask internal technological variability and obscure the complexity of production and exchange systems. This study adopts a bottom-up approach that treats technological traits—such as inclusion type and its density, core firing color, and surface coating color not as attributes of fixed types but as informative indicators of chaîne opératoire variation. Using dimensionality reduction (UMAP) and network analysis, the research aims to uncover patterns of technological similarity, continuity, and divergence among approximately 3,300 ceramic sherds from more than 70 sites in the district of Dashtestan.

### Methods and Materials

Ceramic traits were defined as a composite of four observable attributes that reflect key stages of the chaîne opératoire: inclusion type, inclusion density, core color, and external coating color (Lemonnier 1993). To prepare the data

for computational analysis, these categorical variables were encoded using one-hot encoding, and ordinal variables (e.g., inclusion density) were encoded numerically. Three variants of UMAP (Uniform Manifold Approximation and Projection) were tested to reduce the high-dimensional trait data to a 2D similarity space: (1) Hamming distance UMAP, which captures exact categorical mismatches; (2) Jaccard similarity UMAP, which considers presence/absence of shared traits; and (3) a custom composite UMAP combining Jaccard and Hamming metrics. This method was chosen over linear alternatives such as PCA, due to the categorical and non-Euclidean nature of the ceramic trait data (McInnes, Healy, and Melville 2018). Clustering in the UMAP space was performed using DBSCAN, a density-based algorithm that identifies core groups and isolates technological outliers without the need to predefine the number of clusters.

To scale from the micro-level (individual sherds) to the regional level, a ceramic similarity network was constructed. Each node in the network represents an archaeological site, and weighted edges reflect the average Jaccard similarity of trait profiles across sites. The resulting network was visualized and analyzed using the NetworkX library, with node size corresponding to the number of diagnostic sherds and node color indicating modularity-based communities (Knappett 2013).

### Results

#### 1. Internal Technological Variability

The UMAP embeddings reveal that none of the three dominant ceramic traditions (SMAG.A, SMAG.B, GRECO) form uniform clusters. Instead, each contains internal subgroups that differ in their technological trait combinations. Some clusters are tightly packed, suggesting standardized recipes likely linked to specific workshops or production centers. Other groups show diffuse spreads or overlap with neighboring clusters, indicating flexible production choices and the potential sharing of technological knowledge across traditions.

## 2. Trait-Level Differentiation

Trait-specific analysis reveals several key patterns:

Inclusion type is predominantly grit across all traditions, indicating a shared raw material base and possibly a common understanding of tempering practice.

Inclusion density and core firing color are more diagnostic. For example, one tradition consistently employs dense tempering and pale firing cores, while another shows lower density and darker cores suggesting differences in both preparation and firing environments.

External coating colors further distinguish traditions, with one group favoring uniform light coatings, and another displaying mixed or darker finishes, possibly reflecting functional or aesthetic preferences.

## 3. Typological Continuum, Not Boundaries

When all three types are embedded in a unified UMAP space, they do not collapse into a single cluster, nor do they form entirely distinct groups. Instead, the results display a partial continuum, with some degree of overlap and transitional forms. This finding suggests that typological categories correspond to broadly shared technological systems, but with enough divergence to reflect distinct operational choices and workshop identities. Some technological clusters remain sharply isolated, while others show gradational boundaries implying a spectrum of interaction rather than rigid separation.

## 4. Macro-Scale Network Patterns

The site-to-site ceramic network demonstrates a connected core of sites sharing mixed technological traits and peripheral zones dominated by a single tradition. Certain nodes act as technological brokers—sites where mixed sherd profiles suggest contact or exchange between production groups. In contrast, other sites display insular profiles, reflecting localized and possibly self-contained production. These patterns suggest that the ceramic landscape of region operated as a semi-integrated technological network—neither fully centralized nor fully isolated but composed of interrelated clusters of production and transmission.

## Discussion

This study demonstrates that trait-based embedding and archaeological network analysis offer a powerful framework for understanding the organization of ceramic technology at multiple scales. UMAP captures fine-grained variation in ceramic traits without imposing typological assumptions, while DBSCAN and network modeling help detect clusters, transitions, and spatial patterns in technological behavior.

The findings challenge typological essentialism in ceramic classification. While traditional types such as SMAG.A and GRECO remain useful for broad categorization, the internal variation and overlap between these groups point to dynamic technological systems, shaped by resource availability, workshop traditions and functional demands. Moreover, the presence of transitional clusters and technological brokers supports a model of horizontal transmission and interaction across the region, rather than isolated craft enclaves.

These results contribute to broader debates in archaeological theory about the nature of standardization, the role of communities of practice, and the multiscale dynamics of production and exchange. They also illustrate how computational methods—when paired with archaeologically grounded trait definitions—can offer novel insights into the material and social dimensions of craft.

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## 261. From Web to CAVE: The CAVE-Kompakkt Viewer for Immersive Archaeological Visualization

*Tom Noack (University of Cologne)*

*Daniel Wickerath (University of Cologne)*

The CAVE-Kompakkt-Viewer represents a novel integration of the open-source Kompakkt 3D web viewer into the University of Cologne's CAVE (Cave Automatic Virtual Environment). Developed within the Virtual Campus initiative, the system connects web-based 3D archaeological and cultural heritage resources with immersive visualization technologies. The Virtual Campus of the University of Cologne integrates virtual and augmented reality technologies to create a digital extension of the university's physical environment. Designed to make studying and research more accessible, it provides immersive ways to experience academic spaces, collections, and data—transforming how knowledge is explored and shared (Willmes et al. 2024). Kompakkt provides a web environment for the presentation, documentation, and annotation of 3D cultural heritage objects according to FAIR principles, supporting interdisciplinary work on archaeological and heritage datasets (Eide 2026; Kompakkt Consortium 2025). However, the experience of interacting with 3D data through a browser remains confined to a flat, two-dimensional interface. The CAVE-Kompakkt-Viewer bridges this gap by adapting the established Kompakkt viewing experience to a room-scale, immersive environment.

The aim of the project is not to replicate Kompakkt's web interface, but to extend its visualization capabilities into a true three-dimensional spatial context. Within the CAVE, users can explore artefacts and reconstructions on scale, interact with them in real time, and experience spatial relationships that are difficult to grasp on a computer screen. By combining digital

presentation with immersive exploration, the project supports a more intuitive understanding in both research and teaching.

The CAVE-Kompakkt-Viewer builds upon Unreal Engine 5 and extends the open-source Kompakkt ecosystem with a native CAVE-compatible application. The system architecture allows real-time streaming of 3D models and metadata directly from the Kompakkt repository. The models are displayed within the CAVE in a dynamically generated interface, with the purpose of ensuring that future objects uploaded in Kompakkt can also be displayed. Interaction is provided via tracked controllers (Flysticks) and motion-tracking sensors. These allow users to load and rotate, scale, and reposition models within the virtual space.

Annotation data from Kompakkt can be displayed directly in the CAVE as interactive labels, linking the immersive view back to its semantic web context. In addition to research applications, the viewer was designed with educational workflows in mind. Students can upload their own 3D reconstructions — created, for example, in photogrammetry or modelling exercises — to the Kompakkt platform and subsequently view them within the immersive environment. This creates a seamless workflow from web-based data management to embodied visualization, fostering digital competencies and spatial understanding. Moreover, the CAVE setting allows several participants to explore and discuss 3D objects together in the same physical and virtual space. This shared experience encourages dialogue, collaborative interpretation, and critical reflection directly around the virtual artefacts—an advantage that distinguishes the system from individual VR solutions.

In testing scenarios, a range of archaeological and cultural heritage datasets were displayed, including artefact scans and site reconstructions. The immersive environment significantly improved the perception of scale, depth, and spatial context compared to traditional screen-based exploration. Collaborative sessions with multiple participants further enabled discussions and interpretative analysis directly around the virtual objects.

From a methodological and educational perspective, the project illustrates how digital heritage infrastructures can extend beyond web and desktop contexts into immersive environments that support archaeological research

and university teaching alike. By merging structured archaeological and cultural heritage data with spatial visualization, the CAVE-Kompakkt-Viewer enhances interpretation, fosters interdisciplinary collaboration, and creates new opportunities for experiential research and learning.

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## 302. Beyond Application: Rethinking Spatial Interaction Modelling in Mycenaean Archaeology

*Arete Michalopoulou (University of Cologne)*

This paper advances the discussion of spatial interaction models in Aegean archaeology by examining both their methodological potential and interpretive limits. Focusing on Late Helladic Messenia (ca. 1600–1050 BCE), the study employs computational modelling to explore the evolution of settlements before and during the rise of the Palace of Nestor at Ano Englianos.

Spatial interaction models simulate the movement of people, goods, and ideas within networks of geographical locations. Widely used in modern geography and archaeology to investigate settlement dynamics and the emergence of hierarchical systems (Paliou and Bevan 2016), these models provide a structured framework for exploring how spatial configurations may have influenced political development in Mycenaean Greece.

In the LH II period (ca. 1450–1400 BCE), several Messenian settlements began to expand, culminating in the dominance of Ano Englianos during the LH IIIB period (ca. 1330–1190 BCE). While traditional interpretations associate this process with the unification of regional centers, recent discoveries at Iklaina challenge the assumption of centralized control and suggest a more complex, potentially decentralized political landscape (Cosmopoulos 2019). This study examines how the spatial organization of settlements between the LH II and LH IIIB periods reflects the evolution of political hierarchies, and explores the roles that peripheral centers, such as Iklaina, may have played in this process.

Using GIS mapping tools and gravity-based spatial interaction models of the Rihll and Wilson family, implemented in R, this analysis examines inter-settlement connectivity across the region. The dataset includes both known sites and a small number of predicted “missing” sites introduced to reduce research bias. A series of parameter sensitivity tests were conducted to assess the robustness of model outcomes and to evaluate the extent to which distance-based factors alone can reproduce the known historical pattern of political centralization.

Across all modelling scenarios, a stable pattern of settlement hierarchy emerges: Iklaina consistently appears as a well-connected hub, while Ano Englianos (Pylos)—despite its well-documented archaeological prominence—does not dominate the simulated networks. This divergence between model outputs and the historical trajectory of Messenia is interpreted as a productive analytical insight. It underscores the limits of spatial determinism and clarifies the distinction between structural potential, shaped by geography and connectivity, and historical contingency, shaped by social and political circumstances.

Conducted as part of a master's thesis, this research argues that computational models are valuable not only for what they reproduce but also for what they reveal about the conditions that shaped historical outcomes. In this sense, modelling serves as a conceptual tool for examining the interplay between space, society, and change in the ancient world (Kohler and Van der Leeuw 2007).

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## 310. Playing With Fire? – Fire Simulation as a Tool for Spatial Analysis of Open-Air Sites

*Rebecca Gnau (University of Cologne)*

The Fire Dynamics Simulator (FDS) is an open-source software tool for modelling fire behaviour and smoke movement in fire safety engineering. Previous studies have demonstrated the usefulness of FDS in archaeology through its application in caves (Kedar et al. 2022) and roman houses (Frey et al. 2022), where it has yielded promising initial results. Previously, 3D reconstructions of fires (and fireplaces) were mainly used for aesthetic purposes, such as in museum exhibitions. In addition, traditional research on fireplaces

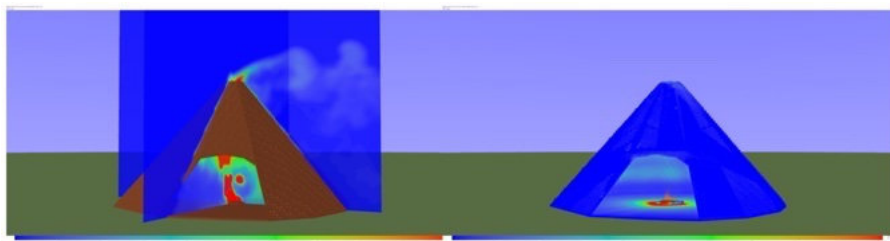
has mainly focused on physical evidence, such as remains of fireplaces, in order to draw conclusions about their structure and functionality (Fuente-Fernández 2022). However, such conclusions are difficult to draw because the functional relationship between documented fire pits and potential protective structures, such as windbreaks or tents, is hard to assess.

The application of FDS to open-air sites enables a quantitative comparison and evaluation of the proposed fire protection combinations in terms of their functionality with regard to heat radiation, light distribution and smoke propagation. Since FDS has not been used for archaeological open-air contexts before, the aim of the work was not only to integrate 3D reconstructions of fireplaces and possible surrounding structures from different contexts, but also to include wind patterns, environmental factors such as temperature, and various materials used in construction. In this regard, particular attention had to be paid to the computational setup, especially the choice of the underlying mesh resolution. The size of the computational grid directly affects the precision with which fire dynamics, turbulence, and heat transfer are represented. Meshes with a higher resolution allow for a more accurate depiction of airflows and temperature gradients but require exponentially greater computational power and memory. As a result, the study confronted the challenge of balancing accuracy and feasibility, seeking a resolution fine enough to capture relevant physical processes while remaining manageable within the constraints of available hardware and simulation time.

Within this technical framework, the case study focused on Palaeolithic settings containing open-air dwellings and hearths reconstructed from archaeological data. The results of the simulations clearly show that different fuel types and hearth constructions produced distinct, quantifiable patterns of heat radiation and smoke movement (see Figure). These findings demonstrate that material selection and hearth design had a considerable impact on the efficiency, comfort, and potential spatial organization around the fire. Beyond the purely physical and functional aspects, the study highlights the fundamental role of fire in human life. Fire not only provided warmth and light but enabled cooking and food processing, creating a social and sensory focal point around which human interaction could unfold. By integrating



physical simulation with archaeological reconstruction, this research contributes to a more nuanced understanding of how people may have experienced and managed fire in open-air contexts. This research shows that the spatial and environmental properties of hearths are inseparable from their social and behavioural significance. Overall, the work demonstrates that FDS can serve as a powerful analytical tool in archaeology, moving beyond its traditional application in enclosed architectural spaces. The combination of experimental reconstruction, computational modelling, and environmental simulation opens new possibilities for assessing the functionality and experiential dimensions of prehistoric fire use.



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### 315. ArchaeoSky: A Quantitative Platform for the Analysis of Astronomical Alignments in the Roman World

*Vasileia Lianou (West university of timisoara)*

#### Introduction

Computational archaeology has advanced methodological approaches and tools to address complex questions about the past. Archaeoastronomy, bridging the humanities and the natural sciences, explores how ancient communities reflected their cosmological beliefs iconographically and architecturally, and whether they oriented built environments towards celestial bodies. In the Roman world, studies suggest symbolic connections between urban planning, imperial propaganda, festivals, and astronomy (González-García et al. 2019, 99). These interpretations integrate geographical and celestial coordinates, trigonometric formulas, statistical analyses, calendar conversions and archaeological sources - a complex interdisciplinary analytical framework.

Despite existing archaeoastronomical computational applications, no tool currently calculates astronomical and calendar data within a single framework, enabling the cross-analysis of these two domains. This is particularly crucial for Roman studies, as the Julian calendar was closely associated with both festivals and potential astronomical orientations. ArchaeoSky bridges this gap as a customizable, open-access and user-friendly computational platform designed for archaeoastronomical analysis of the Roman period. It enables the automatic computation of interdisciplinary data, accuracy, transparency and provides the foundation for the cross-comparison of results.

#### Method

ArchaeoSky (<https://archaeosky.org/>) is a Python-based Flask web platform, designed to analyze the orientations of Roman sites and their potential correlations with solar phenomena, such as the equinoxes and solstices. The platform uses the NASA Jet Propulsion Laboratory NAIF DE431 planetary and lunar ephemerides file (Folkner et al. 2014, 3), from which an .npz file was generated, covering the period of the Roman Empire (27 BCE - 476 CE).

Calculations of Julian Day Number (JDN) are performed using the Skyfield library, while the conversion of values to the proleptic Julian calendar follows Meeus' algorithm.

The platform's philosophy lies in its flexibility, adaptability, and quantitative approach. Each analysis is defined by the user's input parameters: azimuth, latitude, horizon altitude, alignment tolerance, uncertainty, and chronology. The first three are used to compute the geometric declination [ $\sin(\delta) = \sin(\phi) \sin(h) + \cos(A) \cos(\phi) \cos(h)$ ], which determines the corresponding astronomical phenomenon for the site's orientation. By considering the horizon profile, the position of the sun on the celestial equator can be determined more accurately, allowing for more realistic analysis. The uncertainty parameter represents measurement errors derived from in situ and/or geospatial data - while alignment tolerance and chronology allow the calculation of corresponding historical dates.

Once all parameters have been entered and the user requests an alignment analysis, the system outputs the computed declination, a quality indicator (based on the user's uncertainty), and the maximum and minimum values of the sun's declination for the desired year. It also identifies whether the declination lies within or outside the solar range. If the calculated declination is within the solar range, the user can examine more details, such as the correlation of the orientation with specific solar phenomena, the dates according to the proleptic Julian calendar, and the JDN at which the sun's declination falls within the user's tolerance.

## Results

To verify the accuracy of ArchaeoSky, peer-reviewed data from archaeological sites established or reconstructed during the reign of Octavian Augustus in various provinces of the Roman Empire, such as Spain and Italy, were used (González-García et al. 2019, 90-92). The platform successfully reproduced the published declination values ( $\delta_e$ ). An example is provided below.

According to González-García et al. (2019, 116), the Roman city of Petavonium in Spain is oriented towards the solstice and reflects the possible symbolic association of Augustus with the sun. The published data used for validation are as follows:  $\phi$  (latitude) 42.08°, Ae (azimuth) 120.5°, he

(horizon altitude) 0° and a total measurement error of  $\pm 0.75^\circ$  (Table 1). The published  $\delta_e$  (declination) is  $-22.1^\circ$ , while ArchaeoSky, using the same input parameters, calculated  $-22.1294^\circ$ , and a solar minimum declination (winter solstice) of  $-23.70^\circ$  for the year 19 BCE - when Legio X Gemina was stationed at the fort. With an alignment tolerance of  $0.5^\circ$ , the platform displayed the Julian calendar dates 9-15 January and 1-6 December. Each date is accompanied by its corresponding JDN to ensure transparency. These values were verified using NASA JPL's Julian Day Converter (<https://ssd.jpl.nasa.gov/tools/jdc/#/cd>).

| Roman site                          | $\phi$ | Ae     | he    | $\delta_e$    | $\delta$ (ArchaeoSky) |
|-------------------------------------|--------|--------|-------|---------------|-----------------------|
| Augusta Taurinorum (Italia)         | 45.07  | 115    | 2.3   | <b>-15.86</b> | <b>-15.6535</b>       |
| Augusta Pretoria (Italia)           | 45.74  | 68     | 10    | <b>22.4</b>   | <b>22.4474</b>        |
| Carthago (Africa Proconsularis)     | 36.88  | 120    | 0     | <b>-23.95</b> | <b>-23.5749</b>       |
| Leptis Magna (Africa Proconsularis) | 32.6   | 54.5   | 0     | <b>29</b>     | <b>29.2890</b>        |
| Petavonium (Hispania)               | 42.08  | 120.5  | 0     | <b>-22.1</b>  | <b>-22.1294</b>       |
| Valeria (Hispania)                  | 39.8   | 120.75 | -0.25 | <b>-23.3</b>  | <b>-23.3039</b>       |
| Petrisberg (Germania)               | 49.75  | 131    | 1.75  | <b>-23.92</b> | <b>-23.6025</b>       |
| Vesunna (Gallia)                    | 45.17  | 90     | 3     | <b>1.95</b>   | <b>2.1271</b>         |

Table 1: Comparison between  $\delta$  values from González-García et al. (2019) and ArchaeoSky.

## Discussion

The development of ArchaeoSky follows current quantitative and rigorous scientific archaeoastronomical methodologies (Higginbottom & Clay 2016), while respecting the different methodological approaches of each researcher and incorporating historical data that highlight the social dimension of analysis. In this way, it enables a unified computational framework that supports quantitative analysis while incorporating temporal context into interpretation, facilitating the exploration of astronomical patterns and significant dates that may be associated with the design of Roman urban layouts. By using the platform, researchers can conduct customized pilot studies or verify existing hypotheses. Its speed and automation enable large-scale interdisciplinary analyses, such as comparisons between provinces, through site-level analyses, thereby contributing to a broader understanding of Roman astronomical traditions.

ArchaeoSky will include the ability to export results, enhancing transparency and reproducibility and will be tested on understudied provinces of the Roman Empire. The platform will also be integrated into GIS environments, enabling dynamic geospatial analyses and encouraging collaborative research. It provides a reproducible and scalable model for integrating astronomy, history, and computer science that can be adapted to other contexts and contribute to the broader study of cultural heritage.

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### 345. Applying the Image Dimension Measuring System for artifact analysis

*Anna Głód (Polish Academy of Sciences)*

*Aldona Kurzawska (Adam Mickiewicz University)*

*Iwona Sobkowiak-Tabaka (Adam Mickiewicz University)*

*Anita Szczepanek (Polish Academy of Sciences)*

*Marjolein Bosch (Austrian Archaeological Institute, Prehistory Austrian Academy of Sciences)*

Recent advancements in digital technologies have opened new avenues in archaeology, significantly enhancing research methodologies. The adoption of modern digital solutions has become increasingly widespread, primarily due to their ability to streamline processes, reduce time requirements, and improve precision. These technologies not only facilitate the collection of more accurate data but also enable the analysis of larger datasets, thereby broadening the scope of archaeological inquiry. A particularly noteworthy innovation in this context is the use of digital measurement systems, such as the Image Dimension Measuring System (IDMS). Although IDMS has been primarily applied in industrial settings—most notably in quality control and product inspection—it has yet to be widely adopted in archaeological research. In this study, we aim to explore whether IDMS, originally developed to assess the quality of mass-produced objects with high accuracy, can also be effectively applied to the examination of serially made archaeological artifacts.

In our presentation, we seek to investigate the potential of the IDMS by applying it to the study of a substantial collection of serial artifacts, specifically a large assemblage of disc beads (several thousand) made of shells recovered from the Early Bronze Age burials at the Krzyżanowice Dolne site 81. Through this case study, we aim to illustrate the capabilities and benefits of this advanced digital tool within the context of archaeological research. The presentation will address several key issues:

Is it possible to apply a tool designed for industrial quality control (IDMS) to archaeological research?

How precise and reliable is IDMS when applied to fragile, irregular, or degraded archaeological artifacts such as shell beads? Does IDMS significantly reduce the time and labor required for analyzing large assemblages of serial artifacts compared to traditional measurement methods? Can IDMS provide

standardized measurements that facilitate cross-site or cross-cultural comparative studies of the same material type? How can IDMS contribute to understanding standardization and variation in serially made artifacts (e.g., disc beads)? What role might IDMS play alongside other digital technologies (e.g., 3D scanning, photogrammetry) to enhance archaeological interpretation? Measuring and statistically analyzing large numbers of artifacts poses a significant methodological challenge. Traditionally, such analyses rely on manual measurements taken with digital calipers and entered into databases—a time-consuming process that also involves direct contact with often fragile objects. To overcome these limitations, we employed the Image Dimension Measuring System.

This technology enables rapid and highly precise, non-contact measurement of selected features across multiple similar objects, sometimes with a precision that exceeds the practical needs of hand-made artifacts. Measurements are conducted according to pre-defined parameters, and the high-resolution images captured by the system ensure exceptional data accuracy. Using this digital measurement projector, we obtained detailed metrics for the entire bead assemblage within a short time, without exposing the artifacts to risk of damage. Up to 99 objects could be measured simultaneously, with each dataset automatically recorded for individual items and groups.

Moreover, databases are generated automatically based on a simple custom program adapted to the specific shapes of the artifacts, enabling efficient statistical analysis. The use of this system substantially reduced the time required for artifact measurement and data processing. Our results demonstrate that IDMS can be effectively applied to large, multi-element artifact collections—often comprising hundreds or thousands of similar objects—and that it facilitates the rapid extraction and analysis of extensive datasets. This example underscores only one of the many possible applications of IDMS within archaeological research and highlights its potential to enhance both efficiency and analytical rigor in digital archaeology.

## 366. Testimony of Stones: A New Method in Ancient Traffic Analysis

*Murat Dirican (Leiden University)*

*Tuna Kalaycı (Leiden University)*

*Jessica Robkin (University of Central Florida)*

*Martin Steskal (Austrian Academy of Sciences / Austrian Archaeological Institute and Head of Ephesus Archaeological Excavations / Türkiye)*

*Scott Branting (University of Central Florida / Department of Anthropology and Head of Kerkenes Archaeological Excavations / Türkiye)*

Stone architectural elements endure as silent witnesses to human movement. Thresholds, steps, and paving stones retain the physical traces of countless feet and vehicles, offering direct evidence of circulation within ancient cities. Yet archaeology still lacks a quantitative method to measure traffic intensity from these traces. The project *Testimony of Stones: A New Method in Ancient Traffic Analysis* addresses this gap by integrating experimental archaeology, rock mechanics, and computational modeling to translate surface abrasion into measurable indicators of past mobility.

Whereas modern pedestrian studies rely on real-time sensor data, archaeology must interpret physical abrasion accumulated over centuries. This research proposes a novel approach that links controlled laboratory abrasion tests with non-destructive field measurements and agent-based movement simulations. By calibrating the surface wear rate based on the frequency and duration of contact, it can become possible to estimate the number of passes made through a given stone surface.

Two Anatolian sites provide the main case studies: Kerkenes, a short-lived Iron Age city built on granite and granodiorite bedrock in central Turkey, and Ephesus, a long-inhabited Hellenistic and Roman metropolis in western Turkey characterized by marble construction. Their contrasting materials and historical contexts offer an ideal framework for testing the method. The main



research question is whether the magnitude and duration of ancient movement can be estimated from measurable abrasion marks on stone surfaces. Fieldwork at both sites combined archaeological documentation with non-destructive mechanical testing. Existing excavation archives and mobility maps were compiled, and selected features were digitally modeled in 3D. Measurement locations represented both public and private domains—city gates, baths, and palatial complexes as well as thresholds, shops, and domestic entrances. In Ephesus, eleven locations across seven structures were studied; in Kerkenes, seven areas were examined. Ultrasonic Pulse Velocity (UPV) and Schmidt Hammer rebound tests were employed to evaluate stone integrity and strength without sampling damage.

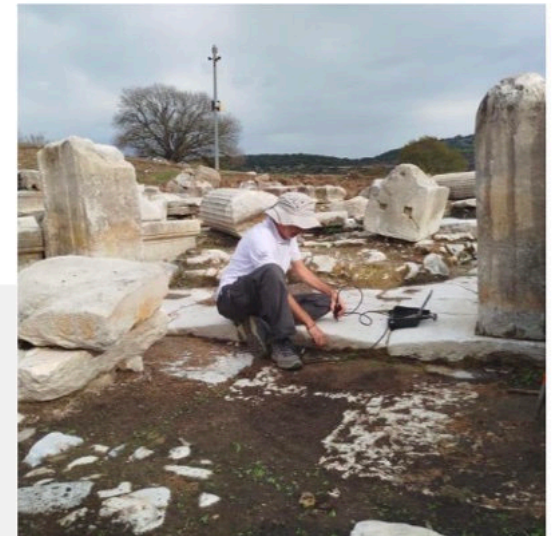
Complementary laboratory analyses were conducted on representative samples collected from local lithologies. In Kerkenes, five granite-granodiorite specimens were tested; in Ephesus, three marble types commonly used in construction were analyzed. Petrographic studies identified mineral composition, while abrasion resistance was measured using the Böhme Abrasion Test (EN 14157; ASTM C241-M). The results were statistically compared to UPV and Schmidt Hammer data to establish correlations enabling abrasion resistance estimation through non-destructive field methods alone.

Preliminary results show strong relationships between material type, abrasion rate, and duration of use. Harder rocks such as granite and granodiorite develop localized, directional abrasion reflecting concentrated traffic, while softer marbles exhibit smoother, more extensive surfaces caused by prolonged exposure. Using experimental calibration, abrasion loss rates (mm/year or mm/step) can be converted into cumulative passage estimates. For example, if laboratory data show that marble abrasions 0.0001 mm per step and a threshold displays 2 mm of abrasion, that surface may represent tens of millions of footsteps. Such quantification allows archaeologists to compare activity levels among urban spaces—temples, streets, shops, and houses—and to reconstruct the dynamics of ancient movement.

The research's final phase integrates these empirical results with Agent-Based Modeling (ABM). Digital simulations of Kerkenes and Ephesus will test how different spatial layouts, social roles, and functional areas influenced

circulation. Virtual agents representing people or carts will move across reconstructed cityscapes, generating traffic density maps that can be compared to measured abrasion data. This approach enables the visualization of ancient mobility patterns and their relation to urban design and social organization.

By merging engineering-based measurements with computational simulations, the research establishes a reproducible, quantitative framework for interpreting ancient use-wear. It transforms static traces of abrasion into dynamic evidence of behavior, bridging the microscopic realm of material alteration with the macroscopic scale of human activity. Beyond archaeological interpretation, the methodology also contributes to cultural heritage management: the same principles can inform risk assessments for visitor-induced abrasion on heritage sites, helping develop preventive conservation strategies such as visitor redirection or surface reinforcement.



### 379. Modeling the Deep Roots of Resilience – A Computational Framework for Organizational Adaptation in Hominin Evolution

*Ericson Hölzchen (Trier University)*

*Veronika Kurchyna (German Research Center for Artificial Intelligence (DFKI), Trier University)*

*Ana Mateos (Centro Nacional de Investigación sobre la Evolución Humana (CENIEH))*

*Jesús Rodríguez (Centro Nacional de Investigación sobre la Evolución Humana (CENIEH))*

*Christine Hertler (ROCEEH Research Center, Senckenberg Research Institute and Heidelberg Academy of Sciences and Humanities)*

*Jan Ole Berndt (German Research Center for Artificial Intelligence (DFKI) and Trier University)*

*Ingo J. Timm (Trier University and German Research Center for Artificial Intelligence (DFKI))*

Human resilience — the ability of a social system to absorb disturbance, reorganize, and maintain function — is a critical, yet often unquantified, aspect of long-term human survival. While computational applications in paleo-research have successfully modeled large-scale demographic events and localized behavioral outcomes, methods of Business Informatics (BI) for operationalizing sophisticated organizational theories, such as dynamic role configuration or complex knowledge management, have been largely inaccessible or inapplicable until now. Integrating these modern methods, however, allows for a substantial enhancement of these existing models, moving them beyond behavioral description.

This paper addresses this gap by proposing a novel, transdisciplinary framework that integrates organizational theory from BI with the empirical data of

human evolution. By treating early human groups as complex adaptive organizations embedded in dynamic environments, we aim to move beyond simple behavioral description towards a mechanistic explanation of human resilience grounded in evolutionary past.

Main argument and resilience framework: We argue that the long-term success of hominin groups in navigating environmental variability was fundamentally dependent on the dynamic interplay between their organizational structure (defined by role configurations) and the efficiency of their knowledge management (Timm et al., 2020). These two factors constitute the measurable foundation of a group's adaptive resilience. Our framework formalizes this relationship in three integrated pillars: (1) organizational structure, which quantifies the ability to rapidly reconfigure roles and division of labor by analyzing different topologies (from rigid, specialized roles to flexible, fluid task assignments); (2) knowledge management, which acts as a driver of resilience and models the transfer and redundancy of critical survival knowledge (e.g., tool making, knowledge about the environment), which is essential for maintaining group cohesion during periods of stress; and (3) adaptive resilience, which integrates these pillars to quantify adaptation success. Resilience is thus defined as a dynamic capability achieved through efficient and timely adaptation of role configurations and available knowledge, allowing researchers to test the optimal "survival heuristics" of past environments.

Methodological transfer: MARL and structured simulation planning. A key contribution is the methodological transfer from Multi-Agent Reinforcement Learning (MARL) to computational archaeology. While Agent-Based Models (ABMs) are widely established in hominin research, the systematic planning and validation of these complex simulations can be enhanced by adopting structured methods from BI. The framework's emphasis on decentralized knowledge and collaborative decision-making directly maps onto principles used in MARL. Furthermore, the search for optimal "survival heuristics" can be formulated as a MARL problem, where agents (hominin groups) learn the



most resilient organizational structures and knowledge management strategies through iterative environmental interaction with a dynamic environment that provides ecological constraints as feedback for the learning process. By applying such structured methods, archaeologists can ensure that their ABMs are explicitly parameterized and designed to test the resilience-relevant mechanisms (organizational structure and knowledge management) of ancient organizational forms, thus elevating the models from descriptive narratives to analytical tools for quantifying adaptive success.

**Computational applications and conclusion:** The primary implication of this framework is its direct utility in enhancing Computational Archaeology, by leading ABMs beyond purely behavioral models towards mechanistic explanations. For instance, we demonstrate the frameworks applicability through a proof-of-concept implementation in a synthetic scavenging environment (Rodríguez et al., 2023) to model how the flow of risk-relevant knowledge within a group minimizes mortality and maximizes success during dangerous high-risk resource acquisition. The framework further allows for the calculation of quantitative metrics typical in BI for organizational analysis (e.g., productivity, throughput, costs), for comparing the adaptive potential of different cultural complexes over long time scales. Crucially, the framework helps non-simulation experts formulate their research questions in a way that allows BI simulation methodologies to be precisely applied to develop models that meet their specific demands. While the foundational idea of transferring BI methods to study hominin evolution has been formulated previously (Timm et al., 2014), the integration of the structured methodological and advanced technological approaches proposed here, particularly with MARL and structured simulation planning, allows these models to be fully realized and significantly enhances our understanding of human evolution and past behavior.

In conclusion, this paper formalizes a generalizable theoretical scaffolding and presents a proof-of-concept implementation, providing a structured methodological approach, providing a framework for transferring BI

methods to analyze the resilience mechanisms of human organizations in the context of their deep evolutionary history.

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## 401. Space time pattern mining: using spatiotemporal analysis for identifying patterns of coin hoarding across the Imperial Roman Empire

*Christina Zymari (Independent)*

The field of archaeology often amasses large datasets with spatial and temporal markers but often only applies basic digital methodologies to analyze and interpret them. This paper introduces Space time analysis applied to a subset of the open access Coin Hoards of the Roman Empire (CHRE) dataset providing a methodological framework for tackling large spatio-temporal datasets using the tools in ArcGIS's Space Time Pattern Mining (STPM) toolbox.

Using coin hoard data from the Roman Imperial period (27 BC and 476 AD) across Europe, the study aggregates a large spatiotemporal dataset into a Space Time Cube and subsequently uses Time Series Clustering and Change Point Detection to cluster locations based on similar hoarding behavior and to find significant shifts of hoarding through time respectively. The results demonstrate that when compared to previously established, qualitatively derived patterns of Roman coin hoarding, the STPM analysis successfully corroborated a significant peak in hoarding during the third century, particularly in regions like Gaul and along the Danube frontier. Correlation clustering of coin hoards in provinces which focused on relative changes grouped regions with low absolute hoard counts (e.g., Achaia, North Africa, Aegyptus, Asia Minor) with high-count regions (Gaul, Danube) based on shared proportional peaks in hoarding intensity. These results not only affirm the tool's potential to recreate known patterns from raw data but also highlight its potential to move beyond changes in simple hoard counts by normalizing the data, and to find new insight that may have been obscured by traditional or basic methods. It also provides a scalable framework for future analysis of large archaeological datasets with spatial and temporal fields by showcasing a practical application for advanced spatiotemporal analysis. The study contributes significant methodological advancements for the study of coin hoards and for digital archaeology more broadly, paving the way for future space-time analysis.

## 452. The use of 3D point densities for archaeological interpretation

*Joshua Emmitt (Auckland Museum)*

*Rebecca Phillipps (University of Auckland)*

*Stacey Middleton (Auckland Council)*

*Simon Holdaway (University of Auckland)*

The application of 3D point density analysis has been a long-term goal, with several earlier attempts presented at CAA International conferences (Emmitt 2018; Emmitt and Masoud-Ansari 2019; Emmitt et al. 2023). This paper will briefly outline previous attempts at the method and the ways our thinking has changed since its first presentation, which started off as a visualisation method and has moved to a more statistical approach. The current methodology is presented along with future directions for this research.

Point density and cluster analysis have a long history in archaeology. Past approaches focus on the identification of clusters of sites on landscape scales, the identification of associated features in excavations, and the grouping of material culture based on typologies or chemical analysis (q.v. Carlson 2017; Sánchez-Romero et al. 2022). Despite this long history and the increase in popularity of 3D applications to archaeological data in the last two decades, there has been little work on the use of 3D density analysis for the association of archaeological objects and features in excavated contexts. The potential for the use of 3D analysis to identify artefact associations and patterns in 3D space provides new ways of examining archaeological deposits. It can be used to create alternative clusters of archaeological phenomena beyond what may have been identified during excavation or associated with stratigraphic layers, by accounting for the wider dispersion of artefacts. In this work, we present the result of a 3D point density analysis using the HDBSCAN clustering algorithm (Campello et al. 2013), executed in R statistics (R Core Team 2021), from two excavations on Ahuahu Great Mercury Island, Aotearoa New Zealand.

Archaeological data from excavations at EA64/66 and EA65 on Ahuahu Great Mercury Island, are used (Holdaway 2024). EA64/66 is a stratified deposit, with radiocarbon determinations from occupation evidence dating from the 14th to the 19th centuries CE. EA65 is a stratified deposit with radiocarbon determinations from the 13th to 15th centuries CE. These areas were excavated in stratigraphic layers, identified through changes in sediment, with the 3D position of each artefact over 2 cm, and the outline and 3D shapes of features recorded with a total station. All material culture types encountered

were recorded with stone artefacts, fire-modified rock, and bone are considered here as the most abundant object types recorded.

A challenge with any cluster analysis, and particularly HDBSCAN is the identification of the minimum number of points that are assigned to a cluster. There is no universal answer to this, and in each case, the number will be contextual depending on the data being analysed, including the kind of material culture is observed and how it was recorded. We apply several statistical cluster validation algorithms (e.g. Convex Hull Volume) to interrogate the data and provide a guide as to the most statistically significant minimum number of points to apply to the algorithm.

Often during excavation, stratigraphic layers are conflated with occupation deposits, identified by changes in sediment, but also by artefact types and the presence of features. The point density analysis examines the density of artefacts from each excavation together, separated by their types to identify potential clusters. These are compared to the stratigraphic features, deposits, and phases identified and interpreted during and after excavation. Preliminary results suggest that while some clusters broadly align with identified features and deposits, there is variability that does not adhere to groupings.

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## S14: Fighting Crime with Computational Archaeology

*Wouter Verschoof-van der Vaart, Netherlands Forensic Institute*

*Hayley Mickleburgh, University of Amsterdam, Faculty of Humanities*

*Mike Groen, Netherlands Forensic Institute*

**Location:** Hörsaal 05

**Session Format:** Standard

In recent decades, countries across the globe have adopted archaeological theories, methods, and techniques within the context of criminal and judicial investigations, for example in the investigation of clandestine or mass graves, buried evidence, human remains, and heritage crimes (Barone & Groen 2025). This use of archaeological theories, methods, and techniques for the investigation of medico-legal and humanitarian cases defines the field of forensic archaeology (Blau & Ubelaker 2016). It involves the systematic documentation, recovery, and interpretation of material evidence, such as human remains, artefacts, and features from outdoor or complex crime scenes, that fall under criminal or legal inquiry.

Criminal investigations are increasingly data intensive, requiring efficient data processing, secure storage, and advanced analytical tools. Like conventional archaeology, forensic archaeology increasingly employs computational methods and techniques, including geospatial analysis and modelling using GIS, geophysical surveying, remote sensing, 3D-scanning, 3D-modelling, augmented reality, and virtual reconstructions. These methods provide important opportunities to efficiently and accurately collect data that meet the strict criteria for legal investigations. For example, a study comparing UAV-based photogrammetry to laser scanning showed near equal accuracy and precision for both methods of 3D data capture, demonstrating the suitability of UAV-based photogrammetry for rapid, non-invasive documentation in hazardous or logistically challenging environments (Cunha et al. 2022).

While the technical requirements and capabilities of computational methods and techniques in forensic archaeological contexts remain largely similar to those in conventional archaeology, forensic archaeology operates within legal frameworks and must adhere to chain-of-custody procedures. The routine application of digital and computational approaches therefore faces specific challenges in forensic contexts, including adaptation to the requirements of law enforcement agency workflows, the necessity for validation of techniques used in legal and judicial procedures, the integration of these

approaches within criminalistics frameworks, and the need for rigorous security measures for sensitive data management.

This session aims to discuss the latest computational developments in the field of forensic archaeology, with particular emphasis on their potential for improving investigative outcomes and to explore how forensic archaeological practice can inform broader archaeology. Due to its fundamental requirements of secure and standardized data handling, careful handling of ethical sensitivities, and strict chain-of-custody procedures, forensic archaeology can offer valuable lessons for developing robust digital practices that benefit broader archaeology.

This session centers on computational innovations applied to or specifically adapted for forensic contexts. We invite contributions surrounding, but not limited to the following major topics:

- Locating, mapping, and visualizing outdoor and/or complex crime scenes such as outdoor scenes, clandestine graves, and mass graves;
- The investigation of heritage crimes (in conflict zones), such as looting;
- Geographical and criminological modeling and the use of geospatial analysis tools such as viewshed analysis and RAG maps within a forensic context.

We ask session presentations to reflect on:

- How forensic contexts affect the requirements of the data itself, procedures for data handling, workflows, etc.;
- Transferable lessons to (and from!) conventional archaeology;
- Gaps in current knowledge and threats to current practice;
- Strategies for standardization and validation of methods and techniques for use in forensic and/or (medico)legal contexts;
- Opportunities to develop open and ethical training resources.

References:

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|               |                                                                                                                                                                                                                                                                                       |
|---------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 11:00 – 11:20 | 242. Searching for clandestine graves in the Netherlands using UAV-based remote sensing<br><i>Wouter Verschoof-van der Vaart (Netherlands Forensic Institute); Eliona Langelaan (Amsterdam University of Applied Sciences)</i>                                                        |
| 11:20 – 11:40 | 311. Predictive Modelling and Modern Clandestine Burials<br><i>Mike Groen (NFI)</i>                                                                                                                                                                                                   |
| 11:40 – 12:00 | 333. Documentation Workflow of the Second World War Mass Grave from Death Valley, Poland<br><i>Jakub Stępnik (Department of Archaeology, University of Warsaw); Dawid Kobiałka (University of Łódź); Joanna Rogóż (University of Rzeszów); Michał Czarnik (University of Rzeszów)</i> |

242. Searching for clandestine graves in the Netherlands using UAV-based remote sensing

*Wouter Verschoof-van der Vaart (Netherlands Forensic Institute)*  
*Eliona Langelaan (Amsterdam University of Applied Sciences)*

Occasionally, so-called clandestine graves are dug by perpetrators to dispose of their victims and to conceal other evidence. Locating these clandestine graves is a necessity for justice to prevail but also to provide the family with answers related to the circumstances of a victim’s death (de Bruyn et al. 2025). Therefore, locating, excavating, and mapping of these graves is one of the main tasks of forensic archaeologists in the Netherlands and abroad. Field searches focus on detecting local surface alterations that can be associated with clandestine graves, including soil color and texture changes, vegetation anomalies, traces of unusual wildlife activity, moisture and temperature changes in the soil, and topographic changes such as depressions and mounds (Koopman, Milliet, and Champod 2025). Currently, different approaches are used by forensic archaeologists and law enforcement to locate victim’s remains in terrestrial outdoor scenes, including line searches and probes, certified cadaver dogs, geophysics, forensic excavations, etc. Yet, these methods are often invasive, expensive, and/or time-consuming. Therefore, UAV-based remote sensing has emerged as a potential non-invasive and low-cost alternative to support the locating clandestine graves (Koopman, Milliet, and Champod 2025). Especially the ability to systematically explore large geographical areas, including potential rough or hazardous terrain, is an important incentive to incorporate these techniques in the forensic (archaeological) toolkit. Consequently, many studies are conducted across the globe to test and validate different UAV-based remote sensing sensors for forensic case work. These studies mainly focus on the use of LiDAR and RGB, thermal, and multispectral cameras (see de Bruyn et al. 2025 for an extensive overview). While LiDAR, and to a lesser extent multispectral cameras (MS) are used in Dutch conventional archaeology to locate and map a variety of

archaeological features, their usability and effectiveness to locate clandestine graves in the Netherlands remains a question. In addition, little is known about the temporal aspect of clandestine grave detection, as well as the influence of weather and seasonality on detectability (see Rocke and Ruffell 2022).

Therefore, in this study a part of a natural burial ground in the Netherlands, containing circa 1000 interments ranging from 2012 onwards was mapped using both LiDAR and MS in the summer of 2022. This particular natural burial ground is considered representative for the majority of clandestine burial locations, as it includes forested, semi-forested, and open grassland areas. The subsoil consists of a coarse sand in which a podzol soil has formed. Considering the ethical, legal, and logistical restrictions on using human donor cadavers the use of natural burial grounds is considered as a valid alternative and a resourceful means for the research into clandestine grave detection (de Bruyn et al. 2025; Rocke and Ruffell 2022). The drone mapping was followed by a GIS-based analysis on the discernibility of graves in both datasets, to determine trends in soil and vegetation anomalies. In addition, at a second test site, graves containing animal carcasses were dug every three months and subsequently mapped with MS in order to investigate the influence of seasonality on the results.

This presentation will present the results of the analyses and the observed trends. It will discuss the complexity of validating UAV-based remote sensing techniques in order for them to have forensically relevant real-world impact, particularly in country specific legal contexts.

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Clandestine Burials." *Forensic Science International*, 112375. <https://doi.org/10.1016/j.forsciint.2025.112375>.

Rocke, B., and A. Ruffell. 2022. "Detection of Single Burials Using Multispectral Drone Data: Three Case Studies." *Forensic Sciences* 2 (1): 72–87. <https://doi.org/10.3390/forensicsci2010006>.

## 311. Predictive Modelling and Modern Clandestine Burials

*Mike Groen (NFI)*

The use of geospatial analysis and predictive modelling, with the aim of discovering new sites through the use of previously known patterns, is widely applied within archaeology. In addition, there are various GIS based studies that show that deposition and dispersal of human remains in modern context is not random (e.g. Congram, 2014; Berezowski et al., 2021; Alegre-Mondragón and Silván-Cárdenas, 2024; Silván-Cárdenas et al., 2024). However, assessing geospatial models to explain and/or predict the occurrence of clandestine burials is sparsely known, and hardly used, within the police and judicial context. This paper presents a study of modern clandestine burials in the Netherlands between the period 1960 and 2025. In doing so, it examines the geographic and geometric behavioral trends in relation to Dutch landscape, types of homicide, victim and offender behavior and clandestine burials. The dataset comes from known Dutch clandestine burial sites and integrates spatiotemporal GIS patterns and Bayes' theorem to predict where, given a certain forensic scenario, an unknown clandestine burial site could be found. The study demonstrates that modern clandestine grave locations are patterned and quantifiable and that geospatial analysis and predictive modelling can be used to help locate missing and presumably clandestinely buried individuals. Locating a clandestine burial site as soon as possible is important, not only to provide the relatives the body of a loved one, but also to prevent taphonomic degradation of human body and other crime scene evidence.



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### 333. Documentation Workflow of the Second World War Mass Grave from Death Valley, Poland

*Jakub Stępnik (Department of Archaeology, University of Warsaw)*

*Dawid Kobiątka (University of Łódź)*

*Joanna Rogóż (University of Rzeszów)*

*Michał Czarnik (University of Rzeszów)*

In 2024, during the second season of excavations in Death Valley, Poland, a mass grave containing approximately 150 individuals was discovered. The excavations were part of a larger research project, The Archaeology of the Pomeranian Crime (Kobiątka 2024a, 2024b; Smykowski & Kobiątka 2023). The project is led by Dr Dawid Kobiątka.

In the first months of the Second World War, German soldiers executed between 20,000 and 30,000 Poles who were considered members of the local social, cultural, or political elites. However, almost anyone could have been targeted for extermination.

A large part of the research concerned the excavations in Death Valley, near Chojnice, Poland. The area outside the town, cut by military trenches, was used as a site to shoot and bury thousands of people. After the war, most of the victims were exhumed, but not all of them were found. Among the missing were patients from a local mental hospital who, in November 1939, were murdered as part of the Nazi campaign to eliminate those deemed “life not worth living” or “empty shells,” according to contemporary propaganda. The individuals were shot and thrown into narrow military ditches, creating multi-level, intertwined mass burials. These circumstances required the adaptation of specific fieldwork methodologies in order to precisely record and analyse the context while maintaining a high excavation speed.

The documentation process consisted of five stages:

1. Exploration, focusing on uncovering as many skeletons as possible while locating all artefacts (bullets, shells, personal belongings) using a metal detector and RTK GPS.
2. Labelling and marking the outlines of individuals, followed by photographic documentation.
3. Photogrammetric documentation of each exploration level.
4. Extraction of the individuals from the mass grave and anthropological analysis.
5. Creating a Digital Double by combining all documentation.

The site formation was complex. The trenches into which the bodies were thrown were narrow, and several layers of intertwined bodies were present. Furthermore, the grave suffered at least four distinct disturbances. Firstly, animals interfered with the upper part of the not-completely-buried grave. After the war, it was partially uncovered, and some remains were removed. Later, the area was levelled with additional soil. A few years ago, a drainage pipeline was dug through the grave, partially destroying it and leaving a pile of bones at the bottom.

Thanks to an experienced team of archaeologists, forensic specialists, anthropologists, and a digital archaeology specialist, we were able to locate, uncover, and methodically excavate the mass grave. The only way to achieve proper documentation was to combine the traditional and well-established exhumation workflow with photogrammetry and digital database creation. This approach led to the creation of a Digital Double, containing 254 GB of spatial data gathered during the excavations. Although it was impossible to fully understand this multi-level grave of commingled bones during fieldwork, it became comprehensible through digital visualisation. All 24 detailed 3D models — including 99 separate individuals and an additional 51 found within the aforementioned pile of bones — were imported into Blender software to create the Digital Double. This enabled a more comprehensive understanding of the grave's formation processes and functioned as a database that spatially organised all associated documentation.

This project demonstrates that implementing advanced yet common methodologies from archaeological excavations into forensic exhumations can not only serve as proof of crimes but also contribute to understanding mass graves in the future. Although it is impossible to identify the individuals due to the perpetrators' efforts to conceal the crime, the grave and its documentation methodology stand as an example of a fast and precise approach to exploring such contexts.

In a time when massive war crimes are being committed, notably in Ukraine, Sudan and Gaza, it is crucial to gather evidence as quickly and precisely as

possible. Therefore, the methodology developed during this project may prove valuable in the future prosecution of perpetrators.

#### References:

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## S15: MuVAMoLa Part Two: Multivariate Approaches to Mortuary Landscapes

*Timo Geitlinger*, University of Zurich

*Tucker Deady*, University of Toronto

**Location:** Hörsaal 02

**Session Format:** Other

*We propose a two-part framework.*

*Part one is in preparation for the conference and includes a submission approximately one month before the meeting of a short summary (this could simply be an adapted abstract) of contributors' overall research and*

*images. The intention is to create an interactive platform to provide conference-goers a prelude to the session. There will be a link in the final program to access this.*

*Part two is the meeting itself which will be structurally akin to a traditional paper workshop of short presentations, creating an environment centered on questions and discussion. To accommodate for more flow and direct conversation, papers will be approximately 7 minutes long and the aim for each will be to focus on a specific method, question, or theoretical topic out of their larger research. The session will be split into themes depending on the topics submitted and each thematic section will have a discussant.*

Mortuary scholarship has perhaps one of the longest histories in archaeological research, but it is a history riddled with bias based on visibility, durability, and public interest. Often most evident in regions where burial practices were accompanied by the erection of monumental architecture, the inclusion of sensational objects, or carry imaginary cultural significance, mortuary contexts have drawn in significant amounts of research. Early scientific endeavors yielded abundant contextual data on burial monuments, ritual behavior, and interred objects. Due to the quality of documentation, however, through locational, temporal and financial predispositions, legacy datasets tend to be heterogeneous and noisy and have large gaps in the types of information collected and recorded (see Cooper et al. 2022). Quantitative analyses of mortuary practices are thus commonly met with specific data-related challenges that have proven themselves obstacles in methodological proceedings. How do we therefore reconcile with this biased history of research while still utilizing the documented material and moving forward into more collaborative conversations within both computational and theoretical scholarship?

Mortuary behavior is inherently linked to individual and group identity and should be seen as both agents creating cultural and social connections *and* manifestations of these relations. Simultaneously, burial construction and material inclusions are highly selective and cannot be taken to represent a daily reality of the associated people (Porter 2016). As archaeologists, we

must ask how we can use the information we gather from burials, intentionally closed contexts, and speak about the living people and the materialization of their self-perception. Likewise, the placement of tombs within specific environments reveals complexities of cultural expressions that permeate past landscapes. The spatial significance of mortuary evidence in association with material culture, when placed under the scrutiny of quantitative analyses, can further enhance the theoretical and methodological approaches to archaeological landscapes as a whole. While early pioneers of computational archaeology conducted quantitative analyses to study burial contexts within individual sites (Hodson 1968), more recent studies use network analysis (Bourgeois and Kroon 2017; Sosna 2023), and principal components and correspondence analyses (Kjeld Jensen and Højlund Nielson 1997; Kassabaum 2011), amongst other multivariate methods (Nakoinz 2013), to study large scale landscape connections of mortuary contexts.

The session is built to bring together scholars from diverse backgrounds who study burials through multivariate quantitative approaches who are interested in discussing qualitative implications, best (and worst) practices, and potential caveats for future scholarship. In this second iteration of MuVA-MoLA, we propose a two-part framework. Part one is in preparation for the conference and includes a submission approximately one month before the meeting of a short summary (this could simply be an adapted abstract) of your overall research and images. The intention is to create an interactive platform to provide conference-goers a prelude to the session with the further goal of turning it into a publishable format. Part two is the meeting itself which will be structurally akin to a traditional paper workshop of short presentations, creating an environment centered on questions and discussion. To accommodate for more flow and direct conversation, papers will be approximately 7 minutes long and the aim for each will be to focus on a specific method, question, or theoretical topic out of your larger research. The session will be split into themes depending on the topics submitted and each thematic section will have a discussant.

We invite authors who:

- Apply and work on multivariate methods to burials and their landscapes
- Develop methodological or theoretical frameworks for the successful application of multivariate and/or spatial methods to study burial contexts.

Please submit a regular length abstract and indicate a specific area you plan to focus on for the conference. Prior to the meeting, we will be in touch regarding your part one submission. We will also be happy to work with session presenters on narrowing their focus for shortened talks and preparing for this discussion-based gathering.

#### References:

Bourgeois, Quentin. and Erik Kroon. 2017. "The Impact of Male Burials on the Construction of Corded Ware Identity: Reconstructing Networks of Information in the 3rd Millennium BC." *PLoS One* (10): e0185971–e0185971. <https://doi.org/10.1371/journal.pone.0185971>

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**11:00 –  
13:00**

- 185. Looking Back to Move Forward: The History of Multivariate Analysis in Mortuary Archaeology  
*Timo Geitlinger (University of Zurich); Tucker Deady (University of Toronto)*
  - 216. Funerary landscape and landscape relationship in the Arabian Peninsula  
*Mathias Bellat (University of Tübingen); Tara Beunzen-Waller (University of Perpignan); Thibaut Guet (University of Perpignan); Sophie*
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*Pébay-Peyroula (Cartodia); Olivia Munoz (UMR 8215 Trajectoires, CNRS)*

- 166. Where the Dead Were Gathered: Tracing the Development of the Early Bronze I Mortuary Landscape at Bab adh-Dhra', Jordan through Geospatial and Multivariate Statistical Analyses  
*Megan Nishida (University of Notre Dame)*
  - 65. Same pots, different people? Exploring the dual burial custom of Westphalia's Funnelbeaker culture  
*Lea Kopner (Universität Münster)*
  - 378. Quantifying Transformation: Multivariate and Bayesian Approaches to Bronze Age Mortuary Change in Central Europe  
*Mirco Brunner (University of Bern)*
  - 283. Early Anglo-Saxon Burials: A multivariate landscape analysis  
*Wyatt Wilcox (University of Oxford)*
  - 206. Resurrecting the Dead (and the Data): The State of Multivariate Analysis in Archaeological Mortuary Research  
*Tucker Deady (University of Toronto); Timo Geitlinger (University of Zurich)*
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## 65. Same pots, different people? Exploring the dual burial custom of Westphalia's Funnelbeaker culture

*Lea Kopner (Universität Münster)*

In the Late Neolithic, the groups of the Funnelbeaker culture (TRB) were the first farming communities to populate the North European Plain where they erected thousands of megalithic tombs. From the turn of the 4th and 3rd millennia, TRB burials also appeared in simple flatgraves. This dual burial custom reflects the beginning of a cultural transformation: While the monumental megalithic tombs were used for collective burials, inhumations in flatgraves focused on the individual. Megalithic tombs represented a long-standing tradition when flatgraves first appeared, whereas the latter were a novelty that went on to become the norm in the following era. It is therefore all the more striking that flatgraves do not seem to have replaced megalithic tombs, but rather that the period of use of megalithic tombs regionally outlasted that of flatgraves by up to 300 years before individual burials reappeared.

The relationship between the two burial types remains unclear. This is in part due to the fact that TRB-flatgraves have been under-researched compared to the monumental megalithic tombs. The only comparative study of TRB-flatgraves to date concluded that it is a regionally highly diverse phenomenon (Kossian 2005). Therefore, this PhD project focuses on their relationship in the area of Westphalia in northwest Germany, which is located on the southern periphery of the TRB-Westgroup. Compared to more central TRB regions, Westphalia has a high density of known flatgrave sites, some of which are located in the immediate vicinity of megalithic tombs, making it an ideal area for a comparison of flatgraves and megalithic tombs. The aim of the project is to determine whether the dual burial custom is an indication of different social groups within the TRB community. Furthermore, as only few traces of the settlements of these groups have survived, an examination of the burial landscape during the TRB period provides valuable insights into the settlement behaviour and social organisation of the first sedentary people in Northern Europe.

Due to the discrepancies in the nature of the burials as well as their preservation, a comparison of the two burial customs is challenging. While megalithic tombs in the area regularly contain preserved bone material allowing

anthropological insights into the deceased, the individual burials are not distinguishable from one another, and the grave goods are highly fragmented and intermixed. Furthermore, megalithic tombs often continue to be prominent markers within the landscape, resulting in continuous activities around them, including secondary inhumations, looting of grave goods and theft of the boulders for use as building material. So, while the amount of finds from one tomb can be incredibly large, there are no closed find situations. Also, it is likely that only a small fraction of the initial number of megalithic tombs remains today. The contents of flatgraves, on the other hand, often remain in situ, allowing to assign well-preserved grave goods to specific burials. However, they are only found by chance, as the grave pits are usually barely visible in the aggressive sandy soils they were built in. This also leads to a lack of organic preservation resulting in a lack of anthropological data and AMS-dates.

To cope with the large gaps of data, the project is divided into GIS-assisted landscape analysis as well as statistical pottery analysis. The spatial distribution and locational factors of TRB burials are analysed to determine whether the same kinds of sites were chosen for megalithic tombs and flatgraves. To assess the reliability of this spatial distribution, two further find categories are plotted in GIS: The first are oral accounts of now-destroyed megalithic tombs. It is likely that some of these accounts are accurate, however, the locational factors of these sites are a lot more diverse than those of the definite tombs, indicating a high error margin. Furthermore, all known TRB stray finds are plotted to check the areas of activity that might have been occluded by bad preservation. While the unverified megalithic tombs and stray finds broaden the Westphalian TRB range, they confirm the overall tendencies of the grave-distribution.

Inhumations took place Westphalia's megalithic tombs for centuries both before and after the flatgrave burials was practised. However, the vast majority of pottery grave goods from megalithic tombs stem from the era that both graves were used, suggesting that most ritual activity within the tombs took place during this period. Furthermore, pottery of the same quality is found in both grave types, which argues against the dual burial custom being a

consequence of social stratification. These factors make pottery the most reliable find group for comparisons. The protected situation within flatgraves allows for more detailed analysis of the pots found in these contexts. These are used to refine the current typology systems and evaluate the interaction of different ornamental elements. Working on from this stage, the comparison of flatgrave and megalithic pottery will focus on the decoration at a lower level rather than the overall ornamentation of a vessel to account for the state of preservation in megalithic tombs. By using multivariate methods such as correspondence and network analyses to determine similarities between different inventories, the level of contact between the people behind both grave types will be assessed.

So far, a tendency of spatial separation suggests a social differentiation behind the dual burial custom that will be further investigated through the analysis of the pottery finds. A possible outcome is that, during the TRB period, Westphalia was populated by two different social groups which at least partially inhabited the same areas and cultivated the same material culture, but did not consider themselves a cultural unit. Findings in this direction will have ramifications not only for the understanding of the social organisation of the TRB but also for the archaeological culture-term.

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#### [166. Where the Dead Were Gathered: Tracing the Development of the Early Bronze I Mortuary Landscape at Bab adh-Dhra', Jordan through Geospatial and Multivariate Statistical Analyses](#)

*Megan Nishida (University of Notre Dame)*



In the Southern Levant, people began to aggregate from small agrarian villages into the earliest walled cities in the Early Bronze Age (EBA, c. 3800/3600-2000 BCE). Bab adh-Dhra', Jordan is one of only two sites in the region to contain a well-excavated fortified settlement and cemetery with an occupational sequence documenting the entire process of urbanization (Rast and Schaub 2003). Beginning in the EB IA (c. 3700-3200 BCE), residents of many dispersed villages buried their dead in secondary, communal interments in subterranean shaft tombs at the site. Mourners in the subsequent EB IB period (c. 3200-3050 BCE) began to modify their relationships with Bab adh-Dhra', building the first permanent village north of the cemetery and creating new above-ground charnel houses. In turn, residents quickly expanded their settlement into an EB II-III (c. 3050-2400 BCE) walled town and continued to bury their dead in even larger charnel houses.

Before EB II-III settlement at Bab adh-Dhra', the EB IA cemetery acted as the central place for shared mortuary practices between a web of mourners and villages. The expansive mortuary landscape, which likely covered an area of approximately 30 hectares, was created through generations of funerary rites and visitations (Kersel and Hill 2020). I investigate how mourners built the cemetery at Bab adh-Dhra' in order to understand ways relationships between EB IA mourners set the stage for the founding of the urban community. Were the dead from multiple agricultural villages buried together in a common area, and then the cemetery expanded as necessary, or did people bury their dead in different areas of the cemetery based on community membership? Did the same village utilize one shaft over generations or did multiple villages construct different chambers off one shaft in a single burial event?

I used a combination of multivariate analysis and GIS-based spatial visualization of tomb locations in the landscape to investigate how cemetery at Bab adh-Dhra' developed. Based on the research by the previous excavators, I employed multivariate and qualitative analyses to date the unpublished EB IA tombs to Early, Middle, and Late phases. Using data from a recent drone survey of Bab adh-Dhra', I estimated the approximate geospatial location of

excavated tombs and used original excavation notes and plans to recreate the shape of tombs in GIS. I added data on grave good, interment practices, and EB IA chronological phasing to ArcGIS to map the development of the cemetery from Early, Middle, and Late phases of the pre-urban EB IA and the proto-urban EB IB. Finally, I used correspondence analysis and univariate testing to visualize the relationships between individual tombs within a given phase.

The results indicate a complex relationship between group differentiation in mortuary practice and chronology among pre-urban groups. While some shafts were only utilized during one period, other shafts contained tomb chambers that belonged to multiple phases, suggesting varying traditions of continuity and renewal. Mourners made specific choices in tomb architecture and types of grave goods that were a result of the relationship between wider communities of mortuary practitioners. This study also highlights the methodological challenges inherent in working with legacy and mortuary collections, where incomplete or inconsistent data required flexible quantitative and spatial approaches.

In addition to studies of early urbanism, this paper also emphasizes the importance of modern geospatial and computational methods to studies of place-making (Silverman et al. 2002). The thousands buried at Bab adh-Dhra' demonstrate the prominence of the cemetery as a regional center. The location and differentiation between tombs in the Early, Middle, and Late EB IA phases and EB IB were foundational to the process of urban formation. The history and development of Bab adh-Dhra's mortuary landscape is a testament to the longstanding communities people created by learning and passing on shared traditions and practices. By employing spatial and quantitative methods, this paper offers insight into the ways people constructed meaningful places through individual and community relationships that served as the foundation for early urbanism in the region.

## 185. Looking Back to Move Forward: The History of Multivariate Analysis in Mortuary Archaeology

*Timo Geitlinger (University of Zurich)*

*Tucker Deady (University of Toronto)*

Multivariate techniques—meaning methods for the simultaneous statistical analysis of more than one outcome variable—are among the most prevalent quantitative methods in archaeology. Within their long history of application, dating back to the 1960s, multivariate analyses of mortuary contexts represent one of the earliest uses. Despite data-related challenges linked to the abundance of legacy datasets tending to be heterogenous, noisy and incomplete in the types of information collected and recorded, burial contexts appear to be particularly suitable for such quantitative approaches. Numerically, they are often abundant enough to yield statistical significance and they typically encompass a multitude of intentional and functional data—arguably making them the richest type of archaeological record unit per volume. As one of the original prototypes of what Montelius termed a “closed find”, objects, human remains, and various environmental proxies have a particularly strong spatial and temporal connection within burial contexts.

The history of application of multivariate techniques in mortuary archaeology can be roughly divided into three phases: Earliest applications—such as Hodson’s (1968) groundbreaking analysis of the Münsingen Rain cemetery—go back to the 1960s. In these early years, multivariate methods were employed both to verify structural correlations, through regression analyses, statistical testing, or early predictive models, and to explore structural relationships. These include earliest examples of factorial, cluster, correspondence, and principal components analysis. All these approaches aligned closely with the positivistic and empiricist thinking of the New Archaeology movement, aiming to make patterns quantitatively plausible relating them to temporal, social, or ethnic phenomena.

With the rise of GIS in archaeology in the 1990s, multivariate approaches were increasingly applied in the context of spatial analysis (Gillings et al. 2020, 11). The growing interest in phenomenology and past spatial decision-making facilitated the use of multivariate techniques to analyse locational factors. This was accompanied by a general shift away from intra-site analyses of mortuary contexts toward consideration of inter-site relations and landscape settings of burial sites. Astonishingly, however, the spatial exploration of non-spatial exploratory multivariate analyses remained rather restricted. Even though they stem from the same family of statistical methods, spatial analysis and first-phase multivariate techniques were often treated as two separate fields in archaeology.

A new set of multivariate approaches bridging this gap between relational and spatial techniques emerged with the rise of network analysis since the 2010s. Being both, inherently spatial and topological, formal network techniques undoubtedly carry great potential for understanding patterns within the mortuary record. Nevertheless, only a limited number of studies on intra- and inter-cemetery networks have been conducted to date (Sosna 2023). In addition to networks, the recent spread of machine learning approaches in computational archaeology has opened new possibilities for applying classical exploratory and regressive, spatial and non-spatial multivariate methods.

Looking back at the history of application of multivariate techniques in archaeology, this paper aims to lay the necessary foundation for envisioning the future of multivariate analysis of mortuary landscapes.

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## 206. Resurrecting the Dead (and the Data): The State of Multivariate Analysis in Archaeological Mortuary Research

*Tucker Deady (University of Toronto)*

*Timo Geitlinger (University of Zurich)*

The past two decades have seen a significant expansion in the use of multivariate and computational approaches within mortuary archaeology. Techniques such as correspondence analysis, social network analysis, and other statistical frameworks have offered new ways to visualize and interpret the relationships between the dead, their assemblages, and the landscapes they occupy. These approaches have begun to alter how archaeologists conceptualize mortuary data – not as static reflections of past social categories, but as complex, relational systems that communicate human decisions, identities, and connections across space and time. Yet, despite methodological advances and a growing sensitivity to theoretical nuance, a persistent gap remains between quantitative analysis and interpretive engagement. The current state of research reflects both a methodological maturation and an ongoing struggle to reconcile statistical modelling with anthropological theory.

The adoption of multivariate methods in mortuary studies has enabled the detection of patterns previously obscured, for example, by descriptive

typologies. Analyses such as Kassabaum's (2011) application of correspondence analysis to burial data in the southeastern United States demonstrate the potential of these techniques to reveal structured relationships between treatment types, age groups, and artifact inclusion. Rather than supporting notions of randomness or cultural uniformity, such results highlight the deliberate, socially embedded nature of mortuary behavior. Similarly, the integration of correspondence analysis within network-based studies has extended this analytical reach. Furholt's work on Corded Ware burials in Europe, for example, shows how multivariate data can be transformed into models of inter-regional interaction, emphasizing the fluidity and multiplicity of symbolic exchange (2014). These and similar studies underscore how quantitative methods have in recent years further illuminated dynamics of identity, mobility, and social differentiation within burial practices.

However, the recent proliferation of quantitative work has not automatically translated into greater theoretical integration. The enthusiasm for computational sophistication often overshadows the interpretive questions that should guide analysis. Sosna (2023) notes that while network-based methods provide a useful framework for conceptualizing relationships among artifacts, mourners, and spaces, they frequently stop short of connecting those relationships to lived experience. This disconnect arises not from a lack of data or computing capabilities but from the difficulty of translating mathematical relationships into social meaning.

This tension exposes a deeper issue within the current state of mortuary research. On one hand, the field has benefitted enormously from a quantitative focus, which has expanded analytical precision, reproducibility, and comparative potential. On the other hand, theoretical engagement has sometimes lagged behind, resulting in a divide between method and meaning. Multivariate analysis, when divorced from theory, risks becoming an exercise in pattern recognition rather than an avenue for exploring human intentionality. Likewise, theory that ignores the structure of data risks drifting into abstraction, detached from the material and spatial realities that

archaeology uniquely provides. Bridging this divide remains one of the most pressing challenges for the discipline.

Some progress has been made toward integration. Researchers are increasingly adopting hybrid frameworks that combine quantitative and qualitative reasoning. For instance, the “practice perspective” advanced by Bourgeois and Kroon (2017) exemplifies how multivariate similarity measures can be used not merely to cluster data but to explore embodied patterns of action and meaning. Their analysis of artifact and body positioning within Corded Ware graves revealed varied communities of practice. This study uses statistical tools as an avenue for theorizing social processes underlying observable patterning.

Nevertheless, the field remains uneven in its update of such reflexive methodologies. Sosna comments that spatial analysis, for example, is still rarely incorporated into network-based models of mortuary behavior, even though burial location and landscape affordances are essential to understanding social memory and place-making (2023, 127). The result is a body of research rich in computational sophistication but still searching for interpretive coherence.

The way forward lies not in abandoning quantitative techniques but in reimagining their role within archaeological reasoning. Multivariate approaches should be understood as heuristic mechanisms. As Munson cautions, analysts must avoid “unnecessary reductionism” (2015, 438) by selecting relational methods that suit both the nature of the data and the theoretical aims of the study. A productive model of integration begins with clear articulation of research questions grounded in social theory, proceeds through rigorous quantitative analysis, and returns to interpretation through the lens, for example, of practice, materiality, or meaning. Such an iterative process transforms multivariate analysis from an end in itself into part of a larger interpretive dialogue.

The current state of research on multivariate approaches to mortuary landscapes is characterized perhaps by imbalance, but also by growth, strength, and inquisitive pursuits. The rise of quantitative modelling has opened new analytical horizons, while the increasing adoption of qualitative and theoretical perspectives has encouraged more human-centered interpretations. Yet the two currents still often run parallel rather than converging. To fully realize the potential of multivariate methods, mortuary archaeology must move towards approaches that treat data and theory as co-constitutive – each informing the other. Mortuary contexts, as some of the most tangible expressions of human cognition and social practices, require this level of integration. The challenge now is not simply to refine computational precision but to create links between measurements of connections and understand why the relationships matter to the people who created them.

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## 216. Funerary landscape and landscape relationship in the Arabian Peninsula

*Mathias Bellat (University of Tübingen)*

*Tara Beunzen-Waller (University of Perpignan)*

*Thibaut Guiet (University of Perpignan)*

*Sophie Pébay-Peyroula (Cartodia)*

*Olivia Munoz (UMR 8215 Trajectoires, CNRS)*

Keywords: Funerary landscape, cairns necropolis, multivariate analysis, environmental covariates, Arabia

### Background:

The Hafit tombs are circular cairns displayed on the ridges lines of low hills to medium mountains. They are clustered in necropolis which can gathered hundreds of tombs and produce a distinctive landscape recognizable over long distances. The Hafit necropolis phenomena started around 3200 BCE (Munoz, 2022), and extent in all over the Arabian Peninsula. Hence, these standardized landmarks were findable over a vast territory and recognizable by various groups over a long period of time (over several millenars). In this study, we want to address the spatial organization of the necropolis in order to extract potential environmental or strategic similarities in necropolis location to understand the functions of those landmarks better.

### Subject:

Arabiancairns project aims to produce two spatial analyses of the funerary landscape, one at the regional scale and three detailed studies on the necropolis. Our dataset comprises 692,370 unique tombs – currently - spread

on the entire Arabian Peninsula. Different covariates, including terrain, ecology, climate, and geology, were collected to produce a multivariate analysis between these variables and the spatial distribution of the tombs (Guiet, 2025; Kwamme, 2020). Pathways and circulation axes will also be explored, with a particular focus on past caravan tracks. Additional geoarchaeological and artefact information will be added at the site scale to draw a closer outlook on the interaction between humans and the environment in a funerary landscape.

### Discussion:

The funerary landscape In the Arabian Peninsula has already been studied at national or regional scales (Deadman, 2017). However, the size of our dataset and our emphasis on human-environment interactions will highlight new elements at a scale which has never been tackled before. By analysing the spatial interrelations between human mortuary practices and their environment, we are able to better understand the funerary landscape for Hafit tombs at the scale of the Arabian Peninsula.

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### 283. Early Anglo-Saxon Burials: A multivariate landscape analysis

*Wyatt Wilcox (University of Oxford)*

During the sixth to seventh centuries AD, Anglo-Saxon England redeveloped social hierarchy and high-status connections with continental Europe in a way that had not been seen since the collapse of Roman administration in the fifth century. The development of social hierarchy in these Anglo-Saxon societies is apparent in the provision of grave goods around the turn of the seventh century. The provision of grave goods to many members of the community stops in the final quarter of the sixth century, and small groups or individuals were commonly buried under barrows alongside many grave goods during the seventh century (Shephard 1979). The shift in grave good provision likely represents a late stage in the formation of the Anglo-Saxon kingdoms.

The study of the landscape may be more productive for understanding social hierarchy than grave goods alone. Semple and Williams (2015) detail how grave goods in Anglo-Saxon graves may be offerings rather than personal possessions of the deceased. While these offerings demonstrate elite social connections, they do not necessarily demonstrate direct choices made on the part of the funeral organizers. However, seventh-century documents such as the Laws of Ine and several Anglo-Saxon Charters demonstrate that landscape use was directed by leading figures in the social hierarchy. The choice of a new cemetery location may have been the direct decision of leading families who had the choice of many possible locations. The location of the cemetery also had the potential to carry meaning for those wishing to commemorate the deceased. Graves from the sixth and seventh century

were often arranged around or placed within prehistoric barrows in a practice intended to forge links with imagined ancestors (Semple and Williams 2015). The Anglo-Saxon cemeteries and newly-built barrows might have also functioned as landmarks that could be both seen and encountered when travelling through the landscape.

Shephard's original insights on the development of social hierarchy were the result of a multivariate study (1979) that analysed grave good numbers, grave good types, and the physical construction of the graves. However, it was not possible to effectively analyse the role of the cemetery as a landmark in 1979, and the landscape was not included in Shephard's analysis. Datasets not available in 1979, such as that of the UK National LiDAR Programme, Aerial Investigation project, and Wiltshire Historic Environment Record, allow important landscape features visible in the sixth and seventh centuries to be recognized with much greater frequency and accuracy. The availability of new data presents an opportunity to use a multivariate analysis to study how the locations of cemeteries in the sixth and seventh centuries changed. In this paper, the question is asked if the physical characteristics of the cemeteries, such their associated earlier monuments, their visibility, and their proximity to routeways, changed at the start of the seventh century along with the changes in grave good provision.

The present study intends to remedy the research gap on the role of the cemetery as a landmark with an analysis of the sixth- and seventh-century cemeteries of Wiltshire. Wiltshire has approximately 94 early Anglo-Saxon cemeteries and isolated barrows, representing a total of around 817 individual burials. The county also contains some of the highest number of identified archaeological features in England. Landscapes used for Anglo-Saxon burials such as Salisbury Plain, the Marlborough Downs, and the South Wiltshire Downs are particularly well-recorded. The cemetery data will initially be categorized and differentiated with a Factor Analysis of Mixed Datasets (FAMD) on landscape data derived from LiDAR scans, the Wiltshire Historic Environment Record, and Historic England's recently-digitized heritage



datasets. The specific data categories include numerical data on topography as well as qualitative data on the characteristics of the associated earlier monuments. The results of the project will illustrate if there is a discernible shift in the topographic preferences of those who built new cemeteries in the seventh century, and if the landscape was a tool used to project the status of those who were commemorated with well-furnished burials as social hierarchy was being redeveloped.

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### 378. Quantifying Transformation: Multivariate and Bayesian Approaches to Bronze Age Mortuary Change in Central Europe

*Mirco Brunner (University of Bern)*

In archaeological research, transformations in material culture and evolving stylistic repertoires are traditionally regarded as primary indicators of socio-cultural change. These observations form the basis for typological classification systems and the definition of chronological phases. In Central Europe, the Bronze Age provides an exceptional framework for examining such transformations, marked by both quantitative and qualitative changes in material culture and burial practices.

This study investigates large-scale shifts in mortuary behaviour and material culture during the second millennium BC, specifically the transition from inhumation burials in flat graves to the emergence of complex tumuli and later to simple cremation burials. The conventional narrative of a linear technological evolution from the Late Neolithic to the Early Bronze Age (EBA), originally defined by Paul Reinecke as phases Bz A1 and Bz A2, has often obscured the probabilistic and multidimensional nature of cultural change.

Here, we apply a combination of regressive reciprocal averaging, Bayesian modelling of radiocarbon-dated grave contexts, and kernel density estimation (KDE) to quantify chronological and cultural transformations in Switzerland and southern Germany. These multivariate approaches allow us to integrate legacy datasets of varying quality and resolution, thereby reconstructing probabilistic trajectories of change in burial practices and material assemblages.

Our results demonstrate a distinct typological and temporal sequence for the EBA phases Bz A1, Bz A2, and Bz B, effectively disproving the long-assumed chronological overlap between them. Moreover, we observe a marked increase in social inequality from the Early to the Late Bronze Age, reflected in the variability of grave goods and funerary architecture, alongside a spatial reorganisation of settlement networks. By combining SPD (Summed Probability Distributions) and Gini coefficient analyses, we quantify these asymmetries and discuss their implications for social differentiation and landscape use.

This study highlights how multivariate quantitative approaches can reconcile heterogeneous burial datasets and provide new insights into the complex

interplay between social transformation, technological innovation, and mortuary behaviour in prehistoric Europe.

## S16: “All Models are Wrong”: Learning from Failure in Computational Archaeology

*Joe Roe, Department of Cross-Cultural Regional Studies, University of Copenhagen, Denmark*

*Matteo Tomasini, Gothenburg Research Infrastructure in Digital Humanities & Department of Literature, History of Ideas, and Religion, University of Gothenburg, Sweden*

**Location:** Hörsaal 05

**Session Format:** Standard

Box’s oft-quoted law—“all models are wrong, but some are useful” (Box 1976)—tells us that the value of a model is not in precisely reproducing the real world, but failing to do so in a productive way. This is nowhere truer than in computational archaeology, the search for mathematical approximations

of a fundamentally unreproducible past. We are voracious producers and consumers of new digital methods, tools, and perspectives (Scollar 1999; Batist and Roe 2024). It is only to be expected that most of these end up going nowhere. Yet only successful models tend to make it into conferences and publications; the lessons we learn from ‘failed’ attempts are kept private. In this session, we call for papers on: models that failed verification, or turned out to be unverifiable; new approaches tried that didn’t work; errors in implementation, large and small; methods and tools that have been left on the wayside; and any other form of failure in computational archaeological research.

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| <b>08:30 –<br/>08:50</b> | 433. Can ecological models predict the occurrence of species in the archaeological record? Can I?<br><i>Joe Roe (University of Copenhagen)</i> |
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| <b>08:50 –<br/>09:10</b> | 68. The rise and fall (and rise again?) of cultural phylogenetics in archaeology<br><i>Felix Riede (Aarhus University)</i> |
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| <b>09:10 –<br/>09:30</b> | 176. Beyond the Signals: A simulation-based evaluation of the Signal Selection Test (SST)<br><i>Alberto Cooper (University of Seville); Enrico Crema (University of Cambridge)</i>                                                  |
| <b>09:30 –<br/>09:50</b> | 224. The Data Strikes Back: Overcoming Challenges in Quantitative Approaches to the Roman Settlement Landscape<br><i>Mark Groenhuijzen (NL); Andrew Lawrence (Universität Bern); Philip Verhagen (Vrije Universiteit Amsterdam)</i> |
| <b>09:50 –<br/>10:10</b> | Discussion                                                                                                                                                                                                                          |

## 68. The rise and fall (and rise again?) of cultural phylogenetics in archaeology

*Felix Riede (Aarhus University)*

I here reflect on the history, fate, failure, and potential for revival of phylogenetic methods in archaeology. Conceived in parallel to the field of evolutionary biology, evolutionary archaeology has been framed as the natural parallel to palaeontology (Mesoudi and O'Brien 2009). The two disciplines do share a range of basic conditions: a fragmented and taphonomically filtered record that is temporally structured; an ambition to reconstruct past environments and lifeways, the challenge of finding historical order and causality. In this context, phylogenetics – the explicit, rigorous, and quantitative mapping of historical relations between the units under study (species, cultures, artefacts, etc.) – has been proposed as the go-to-method for archaeology. In the early 2000s, phylogenetic methods indeed enjoyed considerable popularity. Yet, using bibliometric methods, Matzig et al. (2023) charted the field of evolutionary archaeology and its methods of choice. In so doing,

we showed that phylogenetics has since been eclipsed. The reasons for this decline may, I suggest here, rest partly in evolutionary archaeologists' inability to keep up with methodological developments in phylogenetics as well as in the failure of the method to provide truly convincing results. Against a canvas of key case studies that illustrate the weaknesses and strengths of this approach, I will explore additional reasons for this seeming failure. Building on these, I will also make the tentative argument that cultural phylogenetic's failure may not be terminal. With a well-established toolkit (e.g. Revell and Harmon 2022) that incorporates sophisticated computation and strong Open Science ethics, a wide range of new possibilities have arisen. Vitally, a future of cultural phylogenetics demands that archaeologists up their game in terms of classificatory rigour, data standardisation and sharing, and that the reconstruction of cultural phylogenies is no longer seen as the end goal of such analyses. Instead, phylogenies must be framed as an intermediary step towards additional downstream comparative analysis that seek to reconstruct the order and correlation of key behaviours with each other and with external drivers.

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## 176. Beyond the Signals: A simulation-based evaluation of the Signal Selection Test (SST)

*Alberto Cooper (University of Seville)*

*Enrico Crema (University of Cambridge)*

### Introduction

Since Dunnell (1978) established the style/function dichotomy as analogues of neutrality and selection, archaeologists have borrowed genetic theory and methods to describe assemblage variability.

Neutrality tests, such as the Ewens-Watterson and Slatkin's test, have yielded insightful results (Madsen 2012). Nonetheless, the nature of the archaeological record and cultural evolution raises critical questions about the inferences from these tests: Does departure from neutrality always mean selection? Can cultural transmission biases equate to selection? Could distinct processes lead to equal outcomes (equifinality)? How reliable are these tests given the poor time resolution of assemblages?

We address this gap by evaluating the Signal Selection Test (SST), a statistical method designed to detect selection in genetic time series data (Feder, Kryazhimskiy, and Plotkin 2014). It is a computationally efficient technique, employing a one-sample t-test (the Frequency Increase Test, FIT) to compare the rescaled allele frequency differences between two successive intervals against theoretical expectations under neutrality. It requires at least three time points ("three-time-point" rule), and it flags selection at  $\alpha = 0.05$ .

Its efficiency for archaeological time series, shaped by evolutionary and depositional processes, remains untested. Thus, our research has three objectives:

- To evaluate neutral detection and Type I error (false positives) under unbiased transmission.
- To appraise its statistical power (SSR) when variants undergo selection via two cultural transmission biases: content and conformist bias.
- To critically gauge the confounding effect of temporal structure of assemblages (i.e., time averaging) on the test's performance.

### Methods and materials

We conduct two simulation-based experiments modelling cultural transmission. Both experiments use base parameters: population size ( $N$ ), innovation rate ( $\mu$ ), a burn-in period ( $B$ ), discrete time units ( $t$ ), and a time window size ( $w$ ) for averaging. Thus, we simulate three transmission models:

- 1) Unbiased transmission: naive individuals randomly adopt a variant from the population.
- 2) Content-biased transmission: learners are more likely to adopt a variant with a higher "attractiveness" score ( $1 + b$ ).
- 3) Frequency-biased transmission: learners are more likely to adopt a variant the more common it becomes, modelled with a conformist exponent ( $1 + c$ ).

Each experiment is paired with two temporal deposition schemes: a snapshot regime (fine-grained ideal deposition) and time-averaging regime (coarse-grained, palimpsest deposition).

In Experiment 1, we simulate neutral conditions under both deposition schemes. At equilibrium, we record variants and run the FIT over multiple iterations. We then calculate the Neutral Detection Rate (True Negatives) and the Type I Error Rate (or False Positive Rate, FPR).

In Experiment 2, we introduce one focal variant with a content or conformist bias at equilibrium. We then follow the same procedure as before, and compute the Signal of Selection Rate (statistical power, SSR) and the Type II Error Rate (or False Negative Rate, FNR).

Both experiments are run with a base parameter set, followed by parameter sweeps to observe the confounding effect of each parameter to the test's ability to flag selection. This approach allows us to capture the interaction between cultural evolution and assemblage formation, helping us pin down potential confounding agents in the archaeological record.

### Results

When no selection is at play (Experiment 1) the neutrality hit-rate (non-NA) is consistently high across versions, oscillating around ~99%. On the other

hand, the %NA variants significantly differs between the snapshot (average of 17.2%) and the time averaged models (average of 0%). These findings are consistent when varying parameters, in fact, the lowest NDR score corresponds to shorter time series (t), and it does not fall under ~95%.

In Experiment 2 SST's statistical power was highly contingent on the transmission bias and data structure. For content-biased transmission, the test demonstrated weak power under the snapshot scheme, with a baseline SSR of only 0.18, though power improved with larger population sizes. Time averaging further increased power, with SSR surpassing the 0.90 threshold in moderately large populations ( $N \geq 400$ ). However, this gain came at a severe cost: the proportion of NA variants skyrocketed to over 50%. In stark contrast, the SST consistently failed to detect conformist-biased transmission, with the SSR remaining at or near zero across all parameter sweeps, regardless of bias strength, population size or time scheme.

#### Discussion

The findings from both experiments reveal that SST's utility is defined by a critical tension between accuracy, power and data structure. Experiment 1 established the test's robustness against Type I error. However, the accuracy in snapshot data came at a cost: the "three-time-point" rule systematically excluded nearly 17% of short-lived variants, creating a significant bias. Time averaging resolved this, virtually eliminating non-analysable variants and ensuring high detection rates. Thus, as a reflection of the archaeological record, it provides more accurate but temporally coarse inferences.

Experiment 2 demonstrated that while time averaging improved power to detect content-biased selection in large populations, it did so by rendering over half of variants non-analysable. The binning that saves short-lived neutral variants causes strongly selected variants to fix or go extinct too quickly to be tested ( $< 3$  time points). More critically, the SST proved entirely blind to conformist-biased transmission, as its frequency-dependent dynamics do not generate the monotonic frequency increases the test requires.

Ultimately, the SST is highly reliable when there is no selection, but exhibits severely limited contingent power to detect it. It struggles with the consequences of processes such as drift and selection (rapid fixation/extinction) and possesses a fundamental design flaw for detecting conformist transmission and content-biased transmission in some instances. This underscores that the SST is not a simple test, but a complex instrument whose output must be interpreted and combined with other methods.

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## 224. The Data Strikes Back: Overcoming Challenges in Quantitative Approaches to the Roman Settlement Landscape

*Mark Groenhuijzen (NL)*

*Andrew Lawrence (Universität Bern)*

*Philip Verhagen (Vrije Universiteit Amsterdam)*

This paper documents our attempts to study how the Roman Empire influenced transformations in the settlement landscape of the Kromme Rijn region (the Netherlands). Our goal was to reconcile fine-grained qualitative insights from a handful of intensively studied archaeological sites with the

broader, coarser patterns visible in an extensive regional dataset of archaeological sites and finds. We recognized the immense potential of quantitative approaches to archaeological data, as demonstrated by previous research on the same dataset (e.g. Groenhuijzen 2018). Yet, the precise methodological pathway to understanding the Roman Empire's impact on the settlement landscape remained unclear. While we knew that changes had occurred, such as shifts in landscape organization and building traditions, these characteristics were poorly captured in the available datasets, which focus primarily on find and feature assemblages rather than spatial or structural transformations. This paper delves into two aspects of our research that in particular underwent several iterations before reaching their final, satisfactory shape.

The first issue that we wanted to address is the temporal resolution of our dataset. By default, the Roman Period in the Netherlands is subdivided into six broad subperiods, obscuring finer-scale changes. To address this, we adapted a previously established tool called Chronophage, a method that can be used to reinterpret site chronologies based on the dating of individual find materials, akin to aoristic analysis (Desachy 2016). This enabled us to analyze the data in smaller, 40-year intervals, especially after incorporating the typo-chronology for specific find types (e.g. pottery, broaches, coins) that differ from our dataset's existing chronological framework. For each interval, a total event contribution is calculated based on the timespans of the individual finds, which can be used to determine site presence or absence. Aoristic analysis approaches have become more common in archaeological research, although we quickly realized that best-practices are not yet universally established, and current implementations are often only best-suited to their own particular case studies. In our case, as well, a critical issue in our initial approach was exposed: the lack of a robust method for thresholding event contribution results, which forced us to confront the limitations of both our data and the method itself.

Our first attempt involved setting an absolute minimum threshold for event contributions. This, however, led to undesirable results: some sites appeared as "present" in intervals where we know that they should have been absent.

The issue was that sites with large numbers of finds could push their event contributions above the threshold, even if those finds were poorly dated. Normalizing the results, dividing the event contribution for each interval by the total event contributions for that site, proved to be another failure as it introduced its own biases: it favored the Middle Roman period, where finds have a more precise dating, over the Early and Late Roman periods, where finds often have broader timespans. Furthermore, it risked including poorly dated sites as "present" throughout the Roman Period, when the evidence was simply too vague to justify such a conclusion. Another approach had the same issues, namely setting a percentage-based threshold, for example with a cutoff at 70% of the maximum absolute event contribution for each site. It again privileged the better-dated subperiods, causing the intervals with less chronological precision to disappear from our analysis.

The solution we eventually settled on was an adaptive thresholding system. For each time interval, we calculated the average event contribution across all sites in the region. We then divided this regional average by the maximum regional average observed across all intervals. If, for example, the average event contribution for a given interval was only 20% of the maximum regional average, we adjusted the default 70% threshold for site presence accordingly, setting it at 20% of 70% (i.e. 14%) of a site's maximum event contribution. This adaptive approach accounted for the varying chronological precision across subperiods, ensuring that sites were only marked as "present" when the evidence was robust enough to support such a conclusion. Combined with an absolute minimum threshold, this gave us results that we were able to verify on the basis of the qualitative analysis. Our ordeal shows that there is still a need to be explicit about our choices when applying variants of aoristic analysis, and to continue the search for a common ground of best-practices.

The second aspect that we want to address in this paper is the evolution of our approach to understand settlement transformations from the archaeological find dataset. Our first attempt was to use clustering analyses to identify characteristic find assemblages across different types of sites (e.g., stone-built vs. regular settlements, military vs. civil sites). We hoped to infer



functional or chronological patterns from distinctive find assemblages among groups of sites. Hierarchical clustering analyses were applied on our dataset using both presence/absence of find categories (Jaccard similarity) as well as proportions of find categories (cosine similarity). However, the find dataset was not robust enough to support meaningful clustering, with the clusters seemingly telling us more about the data quality than actual archaeological patterns. Rather than abandoning the quantitative approach entirely, we opted for a more targeted method: focusing our analysis on specific find types that tend to have been recorded accurately and that are known indicators of interaction with Roman networks, namely terra sigillata, coins, stone building materials, and transport pottery. By tracking the distribution of these finds through time, we gained clearer insights in how Roman influence permeated the settlement landscape and could make distinctions between the development of find assemblages from military and civil sites. This iterative process is an example of how validation with the archaeological reality helps to refine the methodological approaches. Each dead end forced a confrontation with the limitations of our data and methods, showing how failure is an essential part of advancing the field. By embracing this process, we not only gained a deeper understanding of the Roman settlement landscape in the Kromme Rijn region, but also developed a methodological framework that can potentially be applied to other regions and periods.

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### 433. Can ecological models predict the occurrence of species in the archaeological record? Can I?

*Joe Roe (University of Copenhagen)*

Ecological niche models, also known as species distribution models, are widely used by ecologists to quantify the relationship between the environment and the geographic extent of an organism (Sillero et al. 2021). Conceptually similar to 'predictive modelling' in archaeology, they involve training a model from known occurrences of the organism and a set of relevant environmental variables at those locations. The trained model can be studied in itself or, more commonly, used to predict the occurrence of the organism in another environmental space. This could be to anticipate the organism's response to future climate change, to model a hypothetical introduction of the organism to a new region or—most interestingly in the present context—reconstruct the palaeodistribution of the organism in a past environment. Franklin et al. (2015) observed a decade ago that the latter application could hold great interest for archaeological research – and also that data from environmental archaeology on known past occurrences could provide a key means of verifying 'hindcasted' ecological niche models. Archaeologists have (with notable exceptions) been relatively slow to take up this call, perhaps due to the difficulty of obtaining the necessary palaeoclimatic data. To my knowledge, there have been no reported uses of archaeological occurrences to verify a hindcast ecological niche model.

In a recent study (Roe and Arranz-Otaegui 2025), I used ecological niche modelling to reconstruct the terminal Pleistocene and Early Holocene biogeography of 65 plant species found regularly in association with early agricultural archaeological sites in West Asia, including the progenitors of the first crops. The scope of the study expanded significantly over the six years I worked on it, presenting technical challenges that were exacerbated by the need to incorporate a large number of 'best practices' drawn from the extensive literatures on ecological niche modelling on the one hand, and

prediction using machine learning on the other. The sense of relief in finally overcoming these challenges and producing models that performed well on all the standard metrics was short-lived, however, because they all spectacularly failed to predict the real past palaeodistributions revealed by the archaeological record. When double- and triple-checking that I did the modelling correctly didn't change the situation, I was forced to invoke Box's law ("all models are wrong, but some are useful," Box 1976) and focus on other insights the results could provide.

Yet reflecting on why these models failed verification has proved, if anything, more interesting than the original study. Is it a failure of this particular model (i.e., is it just my fault)? Or is there a fundamental problem of transferability of ecological niche models applied to the past? In either case, is it possible to rectify the situation? Here I argue that, while methodological improvements could certainly be made, especially to mitigate overfitting, the mismatch between hindcast model and the archaeological record cannot simply be put down to the model being 'wrong'. Instead it prompts us to think more explicitly about what past process—or processes—these two different signals represent and, crucially, how they have been transformed. In particular, both palaeodistribution models (via the palaeoclimate surfaces used to produce them) and environmental archaeology represent temporally "mixed assemblages" (Perreault 2019, 40–79), but mixed in different ways. With this in mind, the expectation that the archaeological record could straightforwardly 'verify' ecological niche models is probably too naive. But it suggests ways in which the two signals could be brought closer together, for example by formally incorporating palaeoclimatic variability and modelling of depositional processes, in a way that would benefit not just environmental archaeology but wider debates on the transferability of ecological niche models (Franklin 2023).

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## S17: Channels of Change – Interdisciplinary Approaches to the Archaeology of Fluvial Environments

*Martin Offermann, Institute for Geography, University of Leipzig, Leipzig, Germany*

*Chiara G. M. Giroto, Labor für Prähistorische Anthropologie, Munich, Germany*

*Iris Nießen, Working Group “Historical Anthropospheres”, LeipzigLab, University of Leipzig, Leipzig, Germany & Department of Medieval Archaeology, University of Tübingen, Tübingen, Germany*

*Lukas Werther, German Archaeological Institute, Romano-Germanic Commission, Frankfurt, Germany*

**Location:** Hörsaal 02

**Session Format:** Standard

Integrating, collating, and holistic interpretation of inter- and transdisciplinary modes of research, evidence, and ideas has long been a part of investigating the past. In recent decades, this approach to archaeological research has been expanded by the ever-growing availability of high-resolution datasets, including satellite imagery, lidar, paleoenvironmental proxies, sediment archives, ancient DNA, isotopic analyses, ethnographic and detailed excavation records. These sources span scales from microscopic material analysis to regional climate modelling, and from single events to processes lasting millennia.

Floodplains are especially suited to such integrative approaches. As dynamic socio-environmental zones where hydrological, geomorphological, and ecological processes intersect with centuries or even millennia of human activity, they preserve exceptional cultural and natural archives. However, in Central Europe up to 95 % of floodplains have been altered or destroyed through embankment, drainage, channelisation, damming, and settlement expansion. These transformations reflect long-term interactions between climate variability, catchment-scale processes, and direct anthropogenic forcing.

Werther et al. (2021) define such heavily modified systems as part of a Fluvial Anthroposphere. The onset of these conditions varies regionally, reflecting environmental settings, historical trajectories, and cultural practices. In Central Europe, major transitions occurred in the medieval and preindustrial periods, driven by intensified land reclamation, hydroengineering, and resource exploitation. Adopting the Fluvial Anthroposphere framework in archaeology means bridging qualitative based evidence (typologies, texts, maps, oral traditions) with quantitative evidence (geomorphological mapping, sediment stratigraphy, palaeohydrological models, geochemistry, biodiversity records). The aim is to create interoperable frameworks that preserve disciplinary focussed approaches whilst enabling joint analysis.

Understanding the long-term coevolution of river systems and societies has practical value for floodplain management, biodiversity conservation, climate adaptation, and heritage preservation. Restoration strategies benefit from recognising that many “natural” baselines are products of centuries of human alteration. Integrating archaeological and historical perspectives ensures such strategies are both ecologically sound and culturally informed.

We invite submissions of case studies, methodological papers, and theoretical reflections from any geographical or chronological context, provided they address the central theme of the session. Possible contributions include but are not limited to:

- Integrating archaeological, historical, ethnographical, stratigraphical, palaeoenvironmental, hydrological, and chronological data into unified models of floodplain formation, transformation, and occupation histories and to reconstruct cultural practices, land-use strategies, and socio-political responses to riverine and floodplain dynamics over centuries or millennia
- Applying quantitative tools to heterogeneous cultural and environmental datasets to identify cross-scale patterns and socio-natural feedbacks.
- Developing visualisation tools that represent multi-scalar and multi-temporal relationships in floodplain and riverine archaeology, integrating both qualitative narratives and quantitative measurements.
- Addressing uncertainty, chronological variability, and error propagation when integrating datasets from diverse disciplinary and methodological origins.
- Reflecting on epistemological and methodological challenges in uniting qualitative evidence with quantitative data, ensuring interpretative balance across disciplines and scales.

Contributions from early-career researchers and projects involving interdisciplinary collaboration across fields such as archaeology, paleoenvironmental science, anthropology, history and computer science are particularly encouraged.

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14:00 –  
14:20

83. Towards a Data-Integrated Understanding of the Fluvial Anthroposphere: Cross-Project Modelling and Classification Frameworks for Central European Floodplains  
*Martin Offermann (Leipzig University); Severin Opel\*; Michael Derntl\*; Geraldine Quénéhervé\*; Vinzenz Rosenkranz\*; Natascha Mehler\*; Iris Ophelia Nießen (Leipzig University, Leipzig Lab); Gerrit Jasper Schenk (Technical University Darmstadt); Lukas Werther (German Archaeological Institute); Christoph Zielhofer (Leipzig University)*

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*\* Tübingen University*

**14:20 – 14:40** 139. The wadi systems of Wadi Abu Dom and Wadi Milik in Sudan – historical hydrology and ancient water management strategies

*Tim Karberg (Universität Münster); Jana Eger-Karberg (Universität Münster)*

**14:40 – 15:00** 205. A GIS approach to digitising the cultural landscape and historical water management of the medieval city Sauran (Kazakhstan)

*Katya Turchin (University College London)*

**15:00 – 15:20** 243. From Experience to Model Parameters: Integrating Experiential Knowledge in Fluvial Archaeological Modelling

*Andrew Mahisa Halim\*; Martin Tomko\*; Adelaide Genay\**

*\* University of Melbourne*

**15:20 – 15:40** 341. Landscape Transformation and Human Response at the Yantra-Danube Confluence: An Interdisciplinary Study of Environmental Change and Settlement Patterns

*Sven Conrad (University of Tuebingen); Nadezhda Kecheva (Archaeological Institute with Museum Sofia)*

**15:40 – 16:00** 398. Identify, characterize, map, and assess fluvial heritage. GIS, database, and atlas on the Saône, Yonne, and Doubs rivers

*Marion Foucher (Inrap-Artehis)*

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**16:00 – 16:30**

414. Study of the landscape: Research in the Mar'e Pontis lagoon, Cabras, Sardinia-Italy

*Maria Mureddu\*; Viviana Pinna\*; Pier Giorgio Spanu (Università degli Studi di Sassari); Rita Auriemma (Università del Salento); Filiberto Chiabrando (Politecnico di Torino); Paolo Orrù (Università degli Studi di Cagliari); Emanuela Solinas (Università degli Studi di Cagliari); Giorgio Murru\*; Anthony Muroi\**

*\* Fondazione Mont'e Prama*

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### 83. Towards a Data-Integrated Understanding of the Fluvial Anthroposphere: Cross-Project Modelling and Classification Frameworks for Central European Floodplains

*Martin Offermann (Leipzig University)*

*Severin Opel (Tübingen University)*

*Michael Derntl (Tübingen University)*

*Geraldine Quénéhervé (Tübingen University)*

*Vinzenz Rosenkranz (Tübingen University)*

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*Iris Ophelia Nießen (Leipzig University, Leipzig Lab)*

*Gerrit Jasper Schenk (Technical University Darmstadt)*

*Lukas Werther (German Archaeological Institute)*

*Christoph Zielhofer (Leipzig University)*

Floodplains are among the most complex and dynamic socio-environmental systems on Earth. Their capacity to preserve both cultural and natural archives makes them uniquely suited to explore the long-term interplay between humans and riverine landscapes. In Central Europe, these systems have been profoundly altered over centuries through embankment, drainage, damming, and urban expansion. These transformations mirror the entanglement of natural dynamics and human interventions. The *Fluvial Anthroposphere* concept (Werther et al. 2021) captures this entanglement, describing floodplains as hybrid systems in which geomorphic, hydrological, and ecological processes are inseparably linked with socio-economic and cultural dynamics. Our work, developed within the DFG Priority Programme (SPP) 2361 “On the Way to the Fluvial Anthroposphere,” builds upon this

framework by integrating archaeological, geoscientific, and historical data into a unified, data-driven research infrastructure.

#### Context

Over the past two decades, archaeology and environmental sciences have undergone a profound data revolution. The proliferation of high-resolution datasets, ranging from satellite imagery and LiDAR to sediment archives, ancient DNA, and isotopic analyses, has expanded our ability to study past landscapes at unprecedented spatial and temporal scales. However, despite these advances, the challenge remains to integrate heterogeneous datasets and disciplinary perspectives into coherent analytical frameworks. Current research often remains fragmented along disciplinary lines, leading to parallel rather than collaborative interpretations of socio-environmental change.

In the context of Central Europe’s floodplains, this fragmentation is particularly problematic. Up to 95% of floodplain areas have been heavily modified, making it difficult to disentangle natural from anthropogenic influences. Moreover, traditional “natural baselines” used for river restoration or conservation planning are increasingly questioned, as many of these landscapes were already profoundly shaped by human activity long before industrialisation. Thus, the concept of the *Fluvial Anthroposphere* requires new methodological tools capable of operationalising human-environmental interactions in quantitative and comparative terms.

#### Research Approach

Our approach aims to bridge this gap by developing an interoperable, spatiotemporal framework for modelling anthropogenic impacts on floodplains during the medieval and pre-industrial periods. Building on the *Spacialist* virtual research environment (Lang et al. 2020), we are implementing a systematic grid-based database that covers the Danube, Elbe, and Rhine catchments. Each raster cell contains linked entries of semi-quantitative indices representing different thematic fields and



across defined time slices. This structure allows researchers from diverse sub-projects to collaboratively enter, compare, and analyse data using a common referential system, thereby enabling both intra- and inter-basin analyses.

Central to our framework are five joint work packages (J-WPs), each representing a dimension of human-river interaction:

1. **Mills** – assessing hydroenergy use as an indicator of technological intensity and landscape modification;
2. **Channel Pattern and Floodplain Land Use** – coupling geomorphological and ecological parameters with socio-economic drivers;
3. **Barriers** – compiling spatially explicit datasets of weirs, sluices, and impoundments to assess connectivity and habitat change;
4. **Fluvio-Social Metabolism of Craft** – reconstructing historical industries and pollutant fluxes to model material and energy exchanges between societies and rivers;
5. **Conflicts** – identifying and classifying water use conflicts to understand governance strategies and socio-natural feedback mechanisms.

The approach is exemplified by the interaction between J-WP2 (Channel Pattern and Floodplain Land Use) and J-WP3 (Barriers). By combining geomorphological and land-use data with systematically catalogued hydraulic structures, we can trace how changes in channel morphology and floodplain utilisation corresponding to phases of intensified water management or ecological degradation. Such analyses may uncover synchronous developments across basins, e.g., regional clustering of weir construction associated with specific land-use regimes, or reveal diachronic shifts in human interventions relative to hydrological thresholds. Initial results point to a negative relation between an increasing number of cumulative barriers as well as increased floodplain land use in contrast to the presence of anadromous fish populations during the past. Finally, sinuous and meandering channel patterns correspond with higher probabilities of anadromous fish presence.

The integration of these dimensions provides a semi-quantitative classification framework for the *Fluvial Anthroposphere*. It enables cross-comparison between catchments and time periods, revealing both shared patterns and regionally specific trajectories of anthropogenic transformation. This joint approach marks a significant step beyond descriptive or site-specific analyses by introducing a structured, scalable model for quantifying socio-environmental interactions.

#### Implications

Methodologically, it represents a model for *FAIR-by-design* research data management in searchaeology and environmental history. By linking qualitative historical sources, such as texts, maps, and oral traditions, with quantitative datasets from geomorphology, geochemistry, and ecology, the framework fosters transdisciplinary interoperability while maintaining disciplinary depth.

From an analytical perspective, the classification model allows for the detection of long-term path dependencies and feedbacks between human practices and fluvial processes. Such insights have direct relevance for contemporary river management, restoration, and conservation policies. Recognising that many “natural” river landscapes are, in fact, historical artefacts of centuries of human engineering helps recalibrate ecological baselines and informs culturally sensitive restoration strategies. Furthermore, by modelling the fluvio-social metabolism of floodplains (Nießen et al. 2025), our approach contributes to broader debates on sustainability and resilience in the Anthropocene.

Beyond its immediate empirical outcomes, the project establishes a methodological and conceptual blueprint for studying other socio-natural systems shaped by prolonged human agency. In doing so, it contributes to a growing movement in digital archaeology and environmental humanities that seeks to bridge disciplinary divides, make complex datasets interoperable, and reframe the human role in landscape evolution as both analytical challenge and opportunity. Moreover, by enabling the recognition of new, sometimes unexpected

spatiotemporal correlations the framework actively fosters the generation of new research questions that move beyond traditional disciplinary boundaries. The resulting framework not only illuminates the historical formation of Central Europe's fluvial landscapes but also informs contemporary debates on how to live sustainably with dynamic riverine environments.

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### 139. The wadi systems of Wadi Abu Dom and Wadi Milik in Sudan – historical hydrology and ancient water management strategies

Tim Karberg (Universität Münster)

Jana Eger-Karberg (Universität Münster)

In Sudan, the Wadi Abu Dom in the Bayuda region and the Wadi Milik in Northern Kordofan belong to the major ephemeral fluvial water bodies. Their hydrology was and is the main driving factor for the development of the cultures and societies along their banks from prehistory until recent times. Two research projects investigated the historical hydrology of these wadis in a geo-archaeological context with different approaches, but resulting in models that provided valuable insights by their combination.

The landscape archaeological approaches of both projects rely on the analysis of TerraSAR-X/TanDEM-X and Sentinel-1 radar satellite data (and DTM based on them), as well as Sentinel-2 multispectral satellite imagery. For palaeoclimatological contextualisation, the TRaCE21ka computation<sup>1</sup> combined with local proxies was used. Analysis methods included the modelling of historical and recent drainage scenarios (combining channel network analysis combined with long-term precipitation modelling in the catchment areas of both wadis), and the reconstruction of aquifers using vegetation analysis. In Wadi Abu Dom, a field survey was complemented by satellite image analysis and landscape archaeological methods but still focusing on on-the-ground research.<sup>2</sup> Subsequent projects have integrated traditional excavations (especially in the micro-oasis of El Rum) with landscape analysis, emphasising the hydrological importance of Wadi Abu Dom as an ecologically favoured zone under varying climatic conditions. This included quantitative analysis of catchment and channel networks (from DTM and radar imagery) and multi-spectral data to identify long-term favoured areas. On-site studies of ancient wells provided insight into the diachronic hydrology of Wadi Abu Dom.

In North Kordofan, research relied primarily on earth observation data, supplemented by targeted ground surveys. Geo-hydrological investigations showed that hafirs,<sup>3</sup> large water-harvesting devices, were the primary hydraulic feature along the Wadi Milik, in contrast to the wells in Wadi Abu Dom. Watershed analysis, contextualised with palaeoclimatic data, was used to understand the use of these technologies under changing ecological conditions.

It became clear during both research projects that greater variability in rainfall and surface water, as is to be expected for the eastern and central Sahel in view of recent climate warming, has also characterised some earlier climate episodes. These included both longer droughts and more intense rainfall and runoff episodes, with a general trend towards increased rainfall. Despite proximity and shared geo- and ecofactors, the regions exhibit significant differences in ancient water management strategies, and this paper explores the reasons for these variations. Research into cultural and socio-economic adaptations to these earlier climate episodes can provide models for how increasing climatic variability and uncertainty can be managed resiliently in the future.

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## 205. A GIS approach to digitising the cultural landscape and historical water management of the medieval city Sauran (Kazakhstan)

*Katya Turchin (University College London)*

Sauran is a large urban settlement in the Kyzylorda region of SW Kazakhstan, located on a sloping alluvial fan between the Syr Darya river and the Karatau mountain belt. It was occupied for over a thousand years, and spread out across two city-sites: Karatobe (6th–13th century) and Sauran (13th–18th century), together covering over 250 ha (Smagulov 2010). Surrounding the cities at an up to 20 km radius is an extensive cultural landscape consisting of intricate agricultural and hydrological features such as field traces, canals, and wells. Water access and the fluctuation of major rivers like the Syr Darya has been a key problem for urbanism in Central Asia since its inception, and continues to be a challenge today. Cities like Sauran had to develop elaborate ways of obtaining sufficient water to survive, and as such provide case studies of longterm resilience to climatic stressors. At Sauran, the kariz hydrological system uses deep wells to access underground aquifers as far as the Karatau piedmont and combines this with snowmelt and rainwater to transport via interconnected lines of wells and canals, directing water towards where it was needed for irrigation. The kariz system resembles the qanats seen elsewhere in Central Asia and Iran, but has some local adaptations suggesting its evolution in response to specific landscape requirements (Clarke et. al. 2005; Sala et al. 2010). The desertification of the area around Sauran means these often ephemeral features are exceptionally preserved and easily visible on satellite imagery. This is in contrast to many other such sites which likely had the same detail, but are located in intensively-cultivated areas, and have lost this visibility and preservation. Although Sauran and Karatobe are protected sites, the features across the landscape are not protected and subject to destruction from construction and development. As such, documenting their full extent is a matter of urgency in terms of

preservation, and provides insights into how such a large city could sustain itself by modifying the landscape around it.

Using QGIS, an intensive high-resolution digitisation was undertaken of Sauran and its cultural landscape, combining publicly-available satellite imagery in conjunction with historical satellite imagery (CORONA), drone photos and derived Digital Elevation Models (DEM), archival material, and previous archaeological research. Over 10,000 features were mapped using a systematic assessment and standardised categorisation, focusing primarily on occupation outside of the city walls to counterpose with existing knowledge on the city itself. Manual digitisation of such a vast landscape offers more value than doing so automatically, as subtle variation between features can be distinguished, especially when features have been damaged and do not directly correspond to what they should look like. As many historical water management features can be confused with more modern soilmarks, an understanding of historical context within the landscape, including how groups of features relate to each other across larger distances, is essential for correct interpretation. The resulting dataset could potentially be used to train a model for improved automatic feature recognition in future.

Analysis of results focused on field traces and hydrological features to understand their development and relation. Several types of field systems were identified, distinguishing between individual plots associated with homesteads vs. larger-scale cultivation which was potentially more centralised. Over a hundred kariz lines were identified and mapped, concurring with previous survey at Sauran, but with much more detail accorded by mapping individual wells, including noting visibility, condition, and risk of damage. This elucidated how the kariz system connected with the canal network and natural watercourses to more easily transport water, and gave an understanding of the landscape's preservation under modern risk from agriculture. An initial phasing was identified based on relations and overlaps of different features visible from the satellite imagery to begin understanding the development of the cultural landscape, particularly that of water management. This phasing will allow further work to study different parts of the landscape to

understand the evolution of occupation. Already it has informed a preliminary survey of priority areas for future sampling, allowing for a focused approach in a hugely varied and detailed cultural landscape, as well as showing the significance of moving beyond a single site, and placing it in context of the broader landscape. This work lays the base for a multiscale study of Sauran, bridging from landscape to microscopic-level by combining geospatial analysis and hydrological modelling with soil sampling and geochemical analysis to understand the resilience of Sauran's hydrological system in a challenging environment for over a millennium.

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### 243. From Experience to Model Parameters: Integrating Experiential Knowledge in Fluvial Archaeological Modelling

*Andrew Mahisa Halim (University of Melbourne)*

*Martin Tomko (University of Melbourne)*

*Adelaide Genay (University of Melbourne)*

Computer simulations have become an invaluable tool for archaeological interpretation, particularly in reconstructing ancient engineering and hydrological systems. Many of these systems were designed to manipulate and

manage water in highly context-specific ways. Through simulation, researchers can attempt to "reverse engineer" these systems, exploring how past societies shaped fluvial environments to meet functional, ecological, and cultural needs. The interpretive potential of these simulations depends on the careful selection of boundary conditions and flow parameters that govern the underlying simulation model. However, due to the uncertain nature of past hydrology and the incomplete archaeological record of ancient structures and flow conditions, determining plausible values of these parameters is challenging.

Current simulation systems require parameters to be specified through textual fields, numerical sliders, or scripts, making the process accessible only to hydrologists and computational modelling experts. Yet archaeologists and traditional custodians often possess deep, experiential knowledge of landscape processes that is tacit, embodied, and spatial rather than quantitative. Existing simulation tools provide few opportunities to integrate this form of expertise into model development. As a result, this knowledge remains underutilised, limiting opportunities for collaborative, cross-disciplinary interpretation of past fluvial systems.

Developments in immersive visualisation and embodied interaction offer promising ways to address these challenges. Virtual Reality (VR) allows users to engage with environment in an embodied manner, replicating the ways we interact with real-world environments. Importantly, it enables individuals with lived or experiential knowledge of water systems to explore simulations in ways that resonate with their past experience of the landscape. This opens up new forms of participatory dialogue: rather than discussing abstract numerical values, collaborators can discuss observable outcomes --- for example, whether a simulated flood extent corresponds with their lived experience or traditional knowledge.

Building on this idea, we propose a VR-based system that integrates hydrodynamic simulation, visualisation, and parameter selection into a single

interactive platform, implemented using the Unity game engine. Instead of specifying boundary conditions and flow parameters as numeric inputs, users can interact directly with the simulated river through embodied gestures in VR. These interactions are translated into simulation parameters, which feed into a simplified shallow-water model running in real time, allowing users to immediately observe the effects of their actions on water flow. This approach enables collaborators without a modelling background to contribute to parameter selection. It also supports the exploration of alternative scenarios, rather than producing a single authoritative reconstruction, better reflecting the uncertain nature of past hydrology.

We demonstrate this system through the study of ancient aquaculture system in south-eastern Australia, showing how VR-mediated exploration of parameter space enables archaeologists, traditional custodians, and modelling experts to collaboratively investigate plausible past scenarios. Ultimately, this approach illustrates how immersive visualisation can bridge disciplinary and epistemic gaps, making computational models more inclusive, participatory, and responsive to the full spectrum of knowledge that informs our understanding of past fluvial engineering systems.

Keywords: Parameter Space Exploration, Immersive Visualisation, Virtual Reality (VR), Computer Simulation

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### 341. Landscape Transformation and Human Response at the Yantra-Danube Confluence: An Interdisciplinary Study of Environmental Change and Settlement Patterns

*Sven Conrad (University of Tuebingen)*

*Nadezhda Kecheva (Archaeological Institute with Museum Sofia)*

The landscape at the confluence of the Yantra River and the Danube—located in the centre of northern Bulgaria—was the focus of a research project funded by the German Research Foundation (DFG) and conducted between 2018 and 2024. The project involved research teams from the University of Tübingen, the National Archaeological Institute with Museum in Sofia, and the KU Leuven.

Aiming to expand and deepen previous research as well as to verify earlier findings, the investigations centred on a cluster of sites at the Tash Bair, a prominent ridge with promontory on the western side of the Yantra estuary, and its surrounding landscape. This strategically favourable location—at the southernmost point of the Danube—was a key intersection of prehistoric and early historic transport routes: east–west along the Danube and north–south along the Yantra. It also served as the start and end point of a direct route connecting the Danube with the Balkan passes, including a favourable river crossing near present-day Svishtov.

Direct access to the Yantra—and thus to the Danube—was a crucial prerequisite for the long-term occupation of the Tash Bair, which was settled as early as the Neolithic period. Furthermore, the mapping of survey data indicates continuous settlement along the river's meanders since at least the

Early Iron Age. Research by the Geography Institute at KU Leuven established that, due to progressive silting caused by ongoing erosion, the meandering main course of the Yantra gradually shifted towards the eastern edge of the lowland terrace around the turn of the first millennium CE. As a result, the settlements and fortifications at the Tash Bair lost direct access to the river. This significant hydromorphological transformation was likely one of the key reasons for the construction of the *latrus* fort in the 4th century CE, as part of the Roman Danube Limes. The fort was established directly on the new course of the Yantra, at the eastern edge of the terrace. Ultimately, the settlement at the Tash Bair was completely abandoned in the early Middle Ages. The research conducted at the Tash Bair and its environs represents the first intensive interdisciplinary study of a micro-region on the lower Danube. Grounded in a robust understanding of regional settlement dynamics, the integration of archaeological fieldwork, GIS-based artefact analysis, and geomorphological investigations enabled a nuanced reconstruction of settlement changes in response to ecological transformations in the study region.

### 398. Identify, characterize, map, and assess fluvial heritage. GIS, database, and atlas on the Saône, Yonne, and Doubs rivers

*Marion Foucher (Inrap-Artehis)*

Rivers are complex objects of study, both linear and composite (floodplain, banks and riverbed), often characterised by a great instability over time. However, a whole variety of purposes has been developed there for thousands of years, and the environment is quite favourable for remains' preservation. Nowadays, rivers are becoming an increasing topic of historical, archaeological, geographical and geological studies. In France, preventive archaeology is also extending its actions to rivers, including banks and riverbeds in its surveys and excavations campaigns.



As a part of three studies conducted by the Inrap (Institut National d'Archéologie Préventive) on the Saône, Yonne and Doubs rivers and the Rhône-Rhine Canal, we sought to develop tools for inventorying, documenting and mapping data. One of the aim is the characterisation of these fluvial areas past uses, one other is to assess the archaeological potential of these floodplains. Past river sites and uses are sorted in a spatial database implemented in a GIS, associated to descriptive atlas developing the historical, archaeological and geomorphological sources used in the study. Together, they form a collaborative workspace that allows for various disciplines and data to interact and discuss, covering long and short time frames and spatial scales .

In addition to providing a detailed overview of poorly documented waterways along their entire courses, these tools are intended retrospectively to help the preservation of archaeological potential, in discussion with regional development and stakeholders (protection services, developers and users). On the Doubs River, for example, the assessment of the potential of both riverbed and floodplain makes it possible to discuss the potential state of preservation – or erosion – of the remains. In an environment characterised by huge changes in river styles, it will help to define the methods of intervention in the field. These tools also contribute to new sites detection, as on the upper Saône River where the combination of bathymetric and underwater surveys with medieval sources has led to the identification of a new fishery. Research projects might exploit these tools' possibilities as well, as in the Ri-BoPAG project (University of Bourgogne Europe), which focuses on watercourses during the Little Ice Age and the adaptation of riverside communities.

These tools are still in development and we are looking forward upgrades linked to the various users' needs, practices and interests. One of the topic we would be interested to discuss is the integration of geological and geomorphological data for a better documentation of in-depth information, allowing an understanding of the filling of the floodplains and underlying archaeological levels as well.

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#### 414. Study of the landscape: Research in the Mar'e Pontis lagoon, Cabras, Sardinia-Italy

*Maria Mureddu (Fondazione Mont'e Prama)*

*Viviana Pinna (Fondazione Mont'e Prama)*

*Pier Giorgio Spanu (Università degli Studi di Sassari)*

*Rita Auriemma (Università del Salento)*

*Filiberto Chiabrando (Politecnico di Torino)*

*Paolo Orrù (Università degli Studi di Cagliari)*

*Emanuela Solinas (Università degli Studi di Cagliari)*

*Giorgio Murru (Fondazione Mont'e Prama)*

*Anthony Muroi (Fondazione Mont'e Prama)*

#### Introduction

The Mont'e Prama Foundation is responsible for the management of the archaeological and natural park of the Sinis peninsula, in central-western

Sardinia (Italy). Its objectives include research, study and documentation initiatives. The three-year project "Water Landscapes. Research in the Mar'e Pontis lagoon", which started in 2024, is lead by the Mont'e Prama Foundation, in collaboration with the University of Sassari and the University of Salento, with the contribution of the University of Cagliari and the Politecnico of Torino.

The project was conceived with the aim of reconstructing the transformations of the Mar'e Pontis lagoon (Cabras, Nurachi, Riola Sardo – Central-West Sardinia, Italy) and the surrounding landscape in a diachronic perspective, using a multidisciplinary approach. The geomorphological aspects concerning the formation of the lagoon and the surrounding water system are taken into consideration, together with the study of the human interaction with the landscape from prehistory until contemporary age.

#### Methods and materials

The research project employs a multidisciplinary approach. Traditional visual land-based and underwater surveys are supplemented by paleoecological sampling and analysis, geophysical surveys (including core drilling), and underwater surveys using tools such as side-scan sonar and magnetometers. Aerial and topographic surveys are also executed. The data obtained are inserted into a Territorial Information System/GIS which also includes the existing literature, the survey cartography, and thematic visibility cartography. The area interested by the research is characterised by very low altimetry, frequently below sea level, sandy shorelines, and by the presence of several waterways, including the Tirso, the main river of the island of Sardinia. These characteristics accelerated the mutation of the landscape and had a great influence in the settlement dynamics. In particular the Mar'e Pontis lagoon is fed by two rivers, the Mar'e Foghe in the North, and the Tanui in the South-East. The same lagoon, that occupied the fluvial valley excavated by the Mar'e Foghe river during the Würm stage, flows into the sea through a complex system of natural and artificial channels.

#### Results and discussion

The underwater survey inside the lagoon was not particularly effective, due to low visibility conditions. At the moment only the detection of anomalies was possible; they will be investigated in the prosecution of the research. The land survey revealed on the contrary numerous points of interest characterised by the dispersion of archaeological materials; this indicates the presence of sites of different chronology along the lagoon shoreline. The occupation starts from the Neolithic period and goes on through Nuragic (Bronze and Iron age), Punic and Roman period, Late Antiquity and medieval times, until modern and contemporary age. It is therefore clear that the water system attracted the human settlement and activities since the start of human occupation of the island of Sardinia and through all times. The area that connects the lagoon to the sea has additional reasons of interest; archaeological, historical and geomorphological data indicate profound transformations of the channel system, and a possible use of the lagoon as a protected harbour during historical times, in particular during Late-Antiquity. The next steps of the research will delve into geophysical analysis, in order to reconstruct the phases of formation of the lagoon and the surrounding landscape. Moreover archaeological excavations in specific points of interest are being planned.



*Figure 1: View of part of the channel system through which the Mar'e Pontis lagoon flows into the sea.*

B. Panico, P.G.Spanu, Archeologia globale dei paesaggi fluviali e costieri della Sardegna: la foce del Tirso e le aree umide del Golfo di Oristano tra antichità e medioevo, G. Volpe, Storia e archeologia globale dei paesaggi rurali in Italia fra tardoantico e medioevo, Bari 2018, pp. 623-648.

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## S19: Structuring the World Beyond: Analytical and Computational Approaches towards Protohistoric and Early Medieval Funerary Data

*Marek Vlach*, Institute of Archaeology of the Czech Academy of Sciences, Brno

*Balázs Komoróczy*, Institute of Archaeology of the Czech Academy of Sciences, Brno

*Marek Hladík*, Institute of Archaeology of the Czech Academy of Sciences, Brno

Katarína Hladíková, Slovak National Museum, Archaeological Museum, Bratislava

**Location:** Hörsaal 01

**Session Format:** Standard

Funerary contexts have long been regarded as a key component of archaeological data for understanding past societies, where burials and funerary areas serve as a bridge between the world of the living and the realm of the deceased (Pearson, 1999). Despite differing perspectives on their potential for shedding light on past societies and their structuring (Tainter, 1978, Binford, 1971, Saxe, 1970, Hodder, 1984, Härke, 2000, Steuer, 1982), they occupy a central role in many theories about social structures, beliefs, and cultural practices. The variability and structure observed in archaeological data on funerary contexts (such as grave furnishings and grave goods) reflect the complex realities of past societies, encompassing the characteristics of the buried individual, their relatives, and the community. Traditionally, archaeologists are primarily examining mortuary remains through qualitative typochronological analysis; however, the available tools and methods, the scale of burial data, and associated natural scientific datasets (e.g., metallography, isotopic analysis, genomics, palaeopathology) enable new and innovative

approaches to analyse both qualitative and quantitative aspects of the mortuary record. Today, advances in computing and digital methodologies are transforming the field, from statistical models to machine learning, enabling the extraction of meaningful patterns from burial context data.

Beyond the traditional “visual” identification of grave clusters, statistical spatial analysis methods such as Ripley’s K-function or kernel density estimation are increasingly used to identify structures and clusters within cemeteries based on objective metrics and hypothesis testing (Sayer, 2020). These results can be further integrated into complex relational models using Structural Equation Modelling (SEM), enabling the testing of hypothetical links between spatial organisation, social factors, and chronology. Such combined approaches can reveal whether cemeteries were organised into small nuclear clusters or large, heterogeneous “households” used over long periods, and can analyse relationships with sex, age, status, or the chronology of the buried individuals.

This session concentrates on computational methods for analysing archaeological and natural scientific data on burial records, focusing on the Protohistoric and Early Medieval periods in Europe (though relevant contributions from other regions and periods are also encouraged). These transitional eras exhibit diverse mortuary practices and extensive burial grounds that greatly benefit from data-driven analysis. The session aims to demonstrate how modern computational archaeology can offer new insights into burial evidence, whether shedding light on social hierarchy, ritual variations, demographic trends, population health standards, or cultural connections across regions. Addressing longstanding questions (e.g., new frameworks to measure prehistoric grave wealth) deepens understanding of how the living world has influenced and extended into the perception of the ‘beyond’ within past societies. In addition to established tools and techniques, the application of artificial intelligence (AI) and machine learning in archaeology can pioneer new frontiers in funerary archaeology, enabling researchers to recognise complex patterns and make predictions that were previously impossible.

Methodologically, the session is open to the full spectrum of computational techniques and tools. We invite researchers to present studies employing any computational methods to analyse burial data. Possible topics and approaches include (but are not limited to):

- Spatial analysis of burial ground layouts, intra-site and/or inter-site spatial analyses, topographic integration, and environmental context
- Chronological modelling of burial sequences through the Bayesian modelling, aoristic analysis, etc.
- Social differentiation through grave goods patterns, including wealth indexing, distributional modelling, and identity metrics across larger datasets
- Multi-proxy integration of archaeometric, bioarchaeological, and environmental data
- Advanced spatial statistics (Ripley’s K-function, nearest neighbour analysis, kernel density) combined with Structural Equation Modelling (SEM) to test hypothetical relationships
- Simulation and network modelling of mortuary behaviour, kin groupings, prestige display systems, and ideological transformation
- Machine learning and AI in various aspects of funerary record archaeological data in classification and pattern recognition
- Meta-analyses or comparative studies of burial practices across cultural, temporal and spatial contexts

By highlighting such diverse approaches, the session will emphasise how these tools and methods can help to address various research questions, transforming raw data from graves into meaningful narratives about past societies. The session aims to foster dialogue between specialists in computational methods and archaeologists working on funerary contexts. We welcome contributions from Europe and beyond, as comparative perspectives can deepen understanding of universal and regional patterns in burial

practices and enhance knowledge of Protohistoric and Early Medieval necropolises.

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| <b>12:20 – 12:40</b> | 63. Beyond the Tombs: Burial Shaft Arrangement as a Mirror of Family Relationships in the Old Kingdom (Abusir, Giza) |
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*Jana Vacková (Charles University); Veronika Dulíková (Charles University)*

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| <b>12:40 – 13:00</b> | 267. Social network analysis for refining the dating of individuals from Old Kingdom Egypt: A case study of the family tree of High Priests of Ptah |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|

*Marek Bukáček (Charles University in Prague); Veronika Dulíková (Charles University in Prague)*

|                      |             |
|----------------------|-------------|
| <b>13:00 – 14:00</b> | Lunch break |
|----------------------|-------------|

|                      |                                                                                                                                                                                       |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:00 – 14:20</b> | 222. From Adornment to Symbolism: The Evolution and Cultural Significance of Turquoise at the Jiahu Site, China<br><i>Zhang Yiwen (University of Science and Technology of China)</i> |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

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| <b>14:20 – 14:40</b> | 422. Modelling burial site distribution: A Machine Learning approach to funerary landscapes in Prehistoric Menorca |
|----------------------|--------------------------------------------------------------------------------------------------------------------|

*Sonia Carbonell Pastor (Barcelona Supercomputing Center); Hèctor A. Orengo (Barcelona Supercomputing Center)*

|                      |                                                                                                                                                                                               |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:40 – 15:00</b> | 255. Connecting demographic agent-based models to skeletal data: the case of the rural Roman cemetery at Tiel-Passewaaij<br><i>Laura van der Knaap*; Philip Verhagen*; Mark Groenhuijzen*</i> |
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*\* Vrije Universiteit Amsterdam*

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| <b>15:00 –<br/>15:20</b> | 148. A.I. = Archaeological Intelligence: Machine Learning-based Post-Diction in the Avar-period Czokorgasse Cemetery at Vienna/AUT<br><i>Dominik Hagmann (University of Continuing Research Krems)</i>                                                                                                   |
| <b>15:20 –<br/>15:40</b> | 435. The Neural Afterlife: Machine Learning Approaches to Reconstructing Roman Period Germanic Societies from Funerary Data<br>Marek Vlach*; Balázs Komoróczy*; Petra Dragonidesová*<br><br>* Czech Academy of Sciences                                                                                  |
| <b>15:40 –<br/>16:00</b> | 98. Bodies, Beliefs, and Bytes: Digital Pathways through Early Medieval Cemeteries<br><i>Nina Richards (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities); Stefan Eichert (Naturhistorisches Museum Wien); Mária Vargha (University of Vienna)</i>                                   |
| <b>16:00 –<br/>16:20</b> | 330. Reconstructing the re-entering of early medieval inhumation graves: 3D GIS for integration and taphonomic analysis of (bio-)archaeological, environmental and geoarchaeological data from high-resolution excavations<br><i>Laura Elmer (Universität Graz); Edeltraud Aspöck (Universität Graz)</i> |
| <b>16:20 –<br/>16:30</b> | Discussion                                                                                                                                                                                                                                                                                               |

## 63. Beyond the Tombs: Burial Shaft Arrangement as a Mirror of Family Relationships in the Old Kingdom (Abusir, Giza)

*Jana Vacková (Charles University)*

*Veronika Dulíková (Charles University)*

Please refer to the PDF version of our abstract, as it includes mathematical notation, figure, and results missing from this plain text version.

### Introduction

The kinship system in ancient Egypt was remarkably stable over millennia. Its significance during the Old Kingdom (c. 2180–2700 BCE) is reflected in the concept of eternal life. Elite members commonly depicted their relatives on the tomb walls or statues, and the arrangement of burial shafts within family tombs or tomb clusters of family clans reveal patterns of kinship and marriage.

Interdisciplinary research into cranial morphology as a kinship indicator has highlighted a notable lack of archeological studies focused on locating burial shafts of individual family members in “family tombs” in the Egyptian Old Kingdom. Only one study (Jánosi 2002) addresses the tomb owner's shaft position, however, limited to the 4th Dynasty period and the Western Cemetery at Giza. Given the sparsity of surviving textual and iconographic sources in the study assemblage from Abusir (predominantly the 5th and 6th Dynasties), it is crucial to examine family relationships from an archaeological perspective. This paper aims to ascertain whether any rules govern the placement of individual family members in the family tombs during the 5th and 6th Dynasties.

### Methods and Materials

#### Egyptological Data



Using our comprehensive MaatBase database containing data on over 9,000 Old Kingdom individuals, their titles, family relations, and burial places, alongside archaeological plans of relevant tombs, we created a list of tombs in Abusir South (excavated by the Czech Institute of Egyptology) and selected tombs in Giza (excavated by Selim Hassan), based on surviving inscriptions referring to the buried individuals. For consistent comparison, the burial shafts were labeled south-to-north (1, 2, 3, etc.). If multiple rows of burial shafts are present, shafts west of the row containing the main shaft are prefixed with 'W', further west with 'WW', and eastward with 'E'. For example, WW3 indicates the third shaft from the south in the third row west of the main shaft. Figure 1 shows the distribution of family relationships in relation to shaft labels.

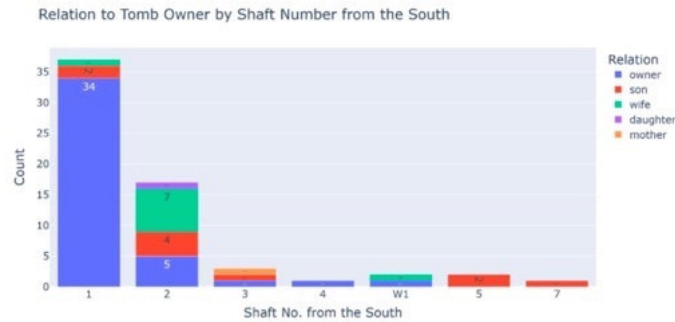


Figure 1: Family relationships and their burial shaft arrangement in Abusir and Giza.

#### Mathematical Model of Family Relations Based on Shaft Arrangement

Since the optimal configuration of family members' burial shafts remains unknown and is the focus of this study, we constructed a set of possible models, which are subsequently evaluated using various metrics.

We adopt the following notation. Let the set of family relations to the tomb owner be denoted by  $F=\{\text{owner}, \text{wife}, \text{son}, \text{daughter}, \text{mother}\}$  and the set of

observed shaft labels by  $S=\{1,2,3,4,5,7,W1\}$ . Many theoretical labels introduced earlier are not present in the data; therefore,  $S$  is simplified accordingly.

The number of unique family relations and shaft labels are denoted by  $n_F=|F|$  and  $n_S=|S|$ , respectively. A model that assigns a shaft label to each observed family relation is expressed as  $f(x)=c_i$ , where  $x \in F$ ,  $c_i \in S$ , and  $i \in \{1,2,\dots,n_F\}$ .

The set of all possible shaft assignments for family members allowing repetition is represented by ordered  $n_F$ -tuples, denoted by  $C=S^{(n_F)}=\{(c_1, c_2, \dots, c_{(n_F)}) \mid c_i \in S\}$ . This means that multiple family relationships may share the same shaft label.

#### Quantification of the Correspondence between the Data and the Model

The correspondence between shaft position and family relationship can be evaluated as both a raters' agreement problem (comparison of two classifying systems) and a clustering task.

From the inter-rater agreement perspective, we use Cohen's kappa ( $\kappa$ ), introduced by (Cohen 1960):  $\kappa=1-(1-p_o)/(1-p_e)$ , where  $p_o$  represents the relative observed agreement of two raters, and  $p_e$  denotes the expected probability of agreement, assuming the independence of the raters.  $\kappa=1$  indicates perfect agreement,  $\kappa=0$  implies agreement no better than by chance, and  $\kappa<0$  detects disagreement.

From the clustering perspective, we evaluate the model's performance using standard metrics such as accuracy, precision, recall, and F1-score (Powers 2011). The group representing tomb owners is substantially larger than those representing other relationships. To ensure fair evaluation, we use macro-averaging of the group-level results (except for accuracy). F1-score, being the harmonic average of both precision and recall, is particularly useful in imbalanced datasets.

#### Results

We evaluated over 16,000 possible shaft arrangement models for family members. Table 1 presents the top 20, ranked in descending order according to Cohen’s kappa.

| Model (family relation: shaft's label)               | With Repetition | Cohen's kappa | Accuracy | Precision | Recall | F1-score |
|------------------------------------------------------|-----------------|---------------|----------|-----------|--------|----------|
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 3}  | Yes             | 0.51          | 0.75     | 0.34      | 0.28   | 0.29     |
| {owner: 1, wife: 2, son: 5, daughter: 2, mother: 3}  | Yes             | 0.49          | 0.71     | 0.40      | 0.39   | 0.33     |
| {owner: 1, wife: 2, son: 2, daughter: 7, mother: 3}  | Yes             | 0.49          | 0.73     | 0.34      | 0.27   | 0.28     |
| {owner: 1, wife: 2, son: 2, daughter: 4, mother: 3}  | Yes             | 0.49          | 0.73     | 0.34      | 0.27   | 0.28     |
| {owner: 1, wife: 2, son: 2, daughter: 5, mother: 3}  | Yes             | 0.49          | 0.73     | 0.34      | 0.27   | 0.28     |
| {owner: 1, wife: 2, son: 2, daughter: W1, mother: 3} | Yes             | 0.49          | 0.73     | 0.34      | 0.27   | 0.28     |
| {owner: 1, wife: 2, son: 2, daughter: 3, mother: 3}  | Yes             | 0.49          | 0.73     | 0.27      | 0.27   | 0.27     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 4}  | Yes             | 0.48          | 0.73     | 0.20      | 0.23   | 0.22     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 7}  | Yes             | 0.48          | 0.73     | 0.20      | 0.23   | 0.22     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 5}  | Yes             | 0.48          | 0.73     | 0.20      | 0.23   | 0.22     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: W1} | Yes             | 0.48          | 0.73     | 0.20      | 0.23   | 0.22     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 2}  | Yes             | 0.48          | 0.73     | 0.20      | 0.23   | 0.21     |
| {owner: 1, wife: 2, son: 2, daughter: 1, mother: 3}  | Yes             | 0.48          | 0.73     | 0.34      | 0.27   | 0.28     |
| {owner: 1, wife: 2, son: 2, daughter: 2, mother: 1}  | Yes             | 0.47          | 0.73     | 0.20      | 0.23   | 0.21     |
| {owner: 1, wife: 2, son: 5, daughter: 4, mother: 3}  | No              | 0.47          | 0.70     | 0.40      | 0.38   | 0.32     |
| {owner: 1, wife: 2, son: 5, daughter: 7, mother: 3}  | No              | 0.47          | 0.70     | 0.40      | 0.38   | 0.32     |
| {owner: 1, wife: 2, son: 5, daughter: W1, mother: 3} | No              | 0.46          | 0.70     | 0.40      | 0.38   | 0.32     |
| {owner: 1, wife: 2, son: 5, daughter: 5, mother: 3}  | Yes             | 0.46          | 0.70     | 0.40      | 0.38   | 0.32     |
| {owner: 1, wife: 2, son: 5, daughter: 3, mother: 3}  | Yes             | 0.46          | 0.70     | 0.33      | 0.38   | 0.30     |
| {owner: 1, wife: 2, son: 7, daughter: 2, mother: 3}  | Yes             | 0.46          | 0.70     | 0.39      | 0.39   | 0.31     |

Table 1: The most suitable 20 models, ranked by Cohen’s kappa.

Discussion

In general, Cohen’s kappa is moderately high, indicating a noticeable agreement beyond chance. Although overall accuracy is relatively high, precision, recall, and F1-score are lower. This is not problematic, as our goal is to compare models rather than evaluate absolute metric performance.

The low values reflect the frequency distribution shown in Figure 1, revealing multiple possible shaft locations for each family relationship. This variability prevents correct classification of all observations. Furthermore, some groups are underrepresented, and the use of macro averages further reduces reported metric values.

For these reasons, we highlight several equally plausible models with similarly high metric values. Thus, no single definitive solution emerges.

Another limitation is the small dataset size. Only more observations could potentially reveal a model that performs significantly better than the others. Specifically, the best-performing models often use variations with repetition, assigning multiple family relationships to the same shaft location. Tomb owners are typically placed in position 1, wives in position 2, and children in the same or subsequent positions. The shaft position of tomb owner’s

mother cannot be reliably considered, as she appears only once in the dataset. Written sources indicate she was usually buried with her husband, unless her status or length of life caused otherwise. To ensure the model is as accurate as possible, it is necessary to consider archaeological context, anthropological findings and written records.

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98. Bodies, Beliefs, and Bytes: Digital Pathways through Early Medieval Cemeteries

Nina Richards (Naturhistorisches Museum Wien/Austrian Centre for Digital Humanities)

Stefan Eichert (Naturhistorisches Museum Wien)

Mária Vargha (University of Vienna)

Introduction

Funerary contexts provide unique insights into social structure, belief systems, and cultural change in past societies. The increasing use of digital methods in archaeology now allows researchers to analyse these contexts at

multiple scales and levels of complexity. Early Medieval cemeteries, in particular, offer dense and multi-layered datasets that combine burial practices, artefacts, anthropological remains, and landscape information. To interpret these data effectively, they must be systematically structured, interlinked, and analysed in a way that bridges qualitative and quantitative approaches. This paper presents a computational and integrative approach to Early Medieval funerary archaeology, centred on three interconnected projects: THANADOS, RELIC, and OpenAtlas. Together, they form a digital research environment for structuring and analysing burial data across regions and disciplines. THANADOS provides a foundation of open-access burial datasets; RELIC (Modelling Religiopolitics – The Imperium Christianum via its Commons) expands this framework by integrating historical, environmental, and textual evidence; and OpenAtlas serves as the database infrastructure enabling structured data modelling, semantic consistency, and multi-proxy analysis.

By linking heterogeneous datasets in a unified environment, these projects demonstrate how digital modelling can reveal patterns of social organisation, religious transformation, and community interaction in the Early Medieval period.

#### Material and Methods

OpenAtlas (<https://openatlas.eu>) is an open-source PostgreSQL-based database system developed by an interdisciplinary team at the Austrian Centre for Digital Humanities (ACDH-ÖAW) and the Natural History Museum Vienna. The system implements the CIDOC Conceptual Reference Model (CIDOC CRM) as its semantic backbone, ensuring interoperability with other datasets. Entities such as sites, graves, burials, artefacts, and osteological information are modelled through relationships, allowing for complex cross-referencing and analysis (Richards et al. 2023).

OpenAtlas enables the creation of datasets suitable for further research. Each record is stored with metadata, linked to controlled vocabularies, and gazetteers such as Wikidata or GeoNames.

thanados.net presents digitized data on Early Medieval burials online. The platform provides open access to standardized burial data through a web interface, where each grave, artefact, and individual is represented as a connected entity with a persistent URL. Users can visualise cemetery layouts, artefact distributions, and burial compositions through interactive GIS plots and analytical charts, facilitating both intra-site and inter-site comparisons (Eichert 2021).

The datapool includes thousands of graves from Austria and neighbouring regions, providing a solid empirical basis for quantitative analysis. Its structure allows for combination of categorical and spatial variables, such as artefact typology, age and sex distribution, and grave orientation.

RELIC (ERC-StG RELIC, 101115501; Vargha and Eichert 2025) expands the THANADOS framework temporally and thematically. It investigates the relationship between Christianisation, social transformation, and landscape organisation across the eastern fringes of the later Holy Roman Empire (10th–12th centuries). To achieve this, RELIC integrates archaeological data with textual sources, topographic information, and environmental proxies.

By linking these different data types within OpenAtlas, RELIC enables a multi-scalar analysis: At a macroscale, it examines how rural churches and cemeteries relate to centres of secular and ecclesiastical power. At a microscale, it explores individual burial assemblages and their potential reflection of religious adaptation, kinship structures, or local identity.

#### Results

The combination of THANADOS and RELIC within OpenAtlas results in a unified and semantically coherent dataset that can be queried across archaeological, textual, and environmental dimensions. This integrated structure enables new computational analyses of funerary data.

Through these analytical capabilities, the datasets move beyond simple cataloguing toward hypothesis-driven exploration. For example, the spatial distribution of richly furnished graves can be compared to proximity to ecclesiastical centres, revealing correlations between burial wealth and Christianisation processes.

The redesigned THANADOS interface will provide interactive tools for visualising cemetery layouts, timelines, and inter-site relationships. Researchers can explore both macro-patterns—such as regional trends—and micro-patterns within individual cemeteries.

All data are accessible under a CC BY 4.0 license, with export options in CSV, GeoJSON, and RDF formats. This ensures transparency, reproducibility, and reuse, while the open-source nature of the system allows adaptation for future projects. Although primarily analytical in purpose, the interface also supports dissemination to a wider public, bridging academic and heritage-oriented audiences.

#### Discussion

Large-scale digital projects in funerary archaeology face a recurring challenge: heterogeneity in data quality and recording standards. Excavations conducted over decades often differ in documentation methods and interpretive frameworks, leading to inconsistencies in classification and chronology. OpenAtlas addresses these challenges by allowing flexible data entry with explicit confidence levels, ensuring that uncertainty and varying precision can be represented transparently.

More importantly, by harmonising data within a consistent structure, the system transforms disparate site reports into a computationally analysable dataset. This opens the door to comparative studies that were previously difficult to achieve. Through statistical, spatial, and network-based methods, burial evidence can be systematically compared across regions and centuries, revealing both local traditions and broader cultural dynamics.

#### Conclusion

The integration of THANADOS, RELIC, and OpenAtlas demonstrates how structured digital recording can advance funerary research beyond documentation toward analysis and interpretation. By combining semantic modelling, open data, and computational methods, this framework enables a comprehensive exploration of Early Medieval cemeteries as dynamic social spaces.

The presentation introduces the three involved projects and demonstrates how they interact, with a particular focus on data entry in OpenAtlas and the subsequent structuring of these data in THANADOS. Visualisation and query capabilities will be emphasised.

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### 148. A.I. = Archaeological Intelligence: Machine Learning-based Post-Diction in the Avar-period Czokorgasse Cemetery at Vienna/AUT

*Dominik Hagmann (University of Continuing Research Krems)*

#### Introduction

Cemeteries represent complex datasets for understanding past societies. They combine biological, social, and material dimensions, yet their interrelations are rarely linear. Recent bioarchaeological work on the Avar-period cemetery from the Czokorgasse in Vienna/AUT (7th–8th century AD; Figure

1) has shown that body height, status, and activity patterns were closely intertwined, reflecting subtle forms of social differentiation (Hermanussen et al. 2025).

This paper explores how artificial intelligence and machine learning (AI/ML) can help understand such relationships. The approach adapts algorithms from ecological niche modeling (ENM) to support archaeological reasoning: Rather than predicting new data, it uses post-diction to examine whether social and biological categories – such as sex, age, or status – display patterned spatial tendencies. The goal is exploratory: to test whether AI/ML methods can reveal internal logics of cemetery organisation that are not readily apparent through conventional spatial analysis.

#### Methods and Materials

The dataset integrates archaeological and bioarchaeological information from several hundred graves ( $n = 774$ ) excavated at the Czokorgasse in Vienna, each recorded for sex, age-at-death, body height, grave depth, and artefact categories such as weapons, ornaments, or equestrian gear. Spatial and contextual data are being prepared in QGIS as a geographic information system (GIS); grave centroids serve as point representations, and selected attributes are converted into continuous raster layers through distance, density, and interpolation functions.

A **presence-only** AI/ML workflow based on the **Maximum Entropy (MaxEnt)** model (Phillips, Anderson, and Schapire 2006) is employed to explore spatial suitability within the excavated area. *MaxEnt estimates the most uniform probability distribution of presences across a defined area, constrained by a set of environmental layers representing spatial and contextual variables relevant to the dataset. Its main advantage lies in its ability to model complex, non-linear relationships from presence-only data without requiring assumptions about absence, making it particularly suitable for heterogeneous archaeological datasets.* This conceptual framework, originally developed for ENM, is here transferred to archaeothanatological analysis, where the ‘niche’ represents the spatial and social suitability of specific burial categories within the cemetery context, defined in relation to a given research

question or hypothesis. Distinct burial categories—for instance, richly equipped female graves or children’s burials—are defined as presences, while the excavated area provides the analytical background. A set of environmental layers, here representing spatial and contextual rather than ecological variables, serves as predictors. These include continuous surfaces derived from grave depth, body height, and age category, as well as distance or density measures relative to other demographic and social groups. However, the approach remains intentionally experimental: it tests whether AI/ML can generate meaningful suitability surfaces that visualize zones of association between social or biological traits.

#### Preliminary Observations

Preliminary exploration suggests that the distribution of attributes within the cemetery is not random. Earlier analyses identified relationships between body height, weapon deposition, and social status among male individuals (Hermanussen et al. 2025). Integrating these parameters into an AI/ML-driven spatial framework may clarify whether such correlations also structure the cemetery at larger scales. Visual inspections already point to possible clustering of richly furnished female graves and peripheral placement of children’s burials – hypotheses to be tested through the forthcoming modeling phase.

#### Discussion

AI/ML-driven methods may function as a bridge between computation and interpretation. By emphasising post-diction, the presented approach seeks to support the interpretation of internal spatial logic rather than to locate unknown features. It converts qualitative impressions – such as perceived clustering or segregation – into probabilistic surfaces that can be visually compared and statistically interrogated.

Crucially, the interpretive value of any suitability map depends on the design of the model itself. What the map depicts – be it spatial tendencies of status, sex, or age – derives entirely from the definition of the target variable (presence) and the choice of predictors. If “high status” is used as the presence

category, predictors directly defining status (e.g., number of weapons) must be excluded to avoid circularity. Instead, independent variables such as body height, grave depth, or distances to other demographic groups may be applied. Each model therefore visualizes only one relational perspective, and meaning arises through comparison between multiple models rather than from a single output.

Furthermore, methodological challenges persist: Spatial autocorrelation among predictors can inflate variable contributions, and the interpretive transparency of the AI/ML-based results must remain central. Yet even at an exploratory level, such modeling can clarify degrees of social affinity, identify transition zones, and formalize intuitive hypotheses about cemetery organization.

Beyond technical experimentation, this work joins wider discussions on the epistemology of AI in archaeology. As Gattiglia (2023) notes, ML should extend – not replace – interpretive reasoning. The proposed framework thus treats AI/ML as a heuristic device: a way to test, visualise, and refine archaeological hypotheses within a transparent analytical context.

## Conclusion

Applying AI/ML-driven approaches to funerary data remains, as in the current case, somewhat experimental but promising. By transferring methods originally meant for prediction to post-diction, the approach focuses on explanation rather than discovery, integrating bioarchaeological and contextual factors into spatial suitability surfaces. These maps may ultimately support comparative studies of cemetery organization, social hierarchy, and identity expression across Protohistoric and Early Medieval Europe.

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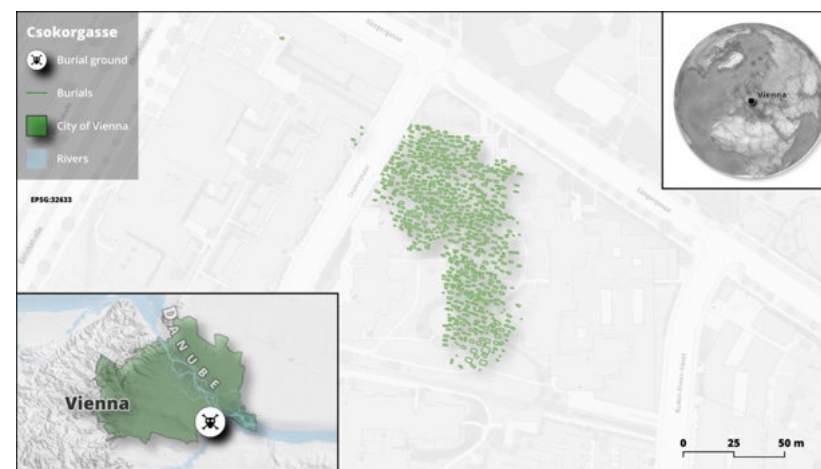


**Figure 1:** Location and spatial distribution of burials at the Avar-period cemetery of Czokorgasse, Vienna (7th–8th century AD). The main map shows the individual graves analyzed within the excavated area; inset maps indicate the position of the site within the modern city of Vienna and its location in Europe (Data sources: Stadtarchäologie Wien, Natural Earth, Land



Niederösterreich, Stadt Wien, Bundesamt für Eich- und Vermessungswesen, basemap.at).

## 222. From Adornment to Symbolism: The Evolution and Cultural Significance of Turquoise at the Jiahu Site, China

*Zhang Yiwen (University of Science and Technology of China)*

The Jiahu site (9000–7500 BP) is a significant Neolithic site in the Henan province in central China. It is famous for the oldest playable musical instruments all over the world and the earliest writing sign in China. During the eighth excavation in 2013, over 2000 turquoise artifacts were unearthed, representing the earliest and largest-scale turquoise artifacts in the world. This paper brings data from all eight excavations of the Jiahu site. Using basic statistics, Chi-square tests, T-tests, and algorithm of mining association rule based on apriori, we examine the number, form, and location of turquoise, as well as their relationship with other artefacts in burials. The results indicate that almost all turquoise items came from burials, especially in the central area of the site. Their number increased largely from phase I to phase II, and dropped sharply in phase III, perhaps due to resource shortage or cultural change. The presence of turquoise in burials is not random. It correlates significantly with the phase and age, with no association to sex. Specifically, turquoise is more likely to be found in earlier phases and with younger individuals. Combined with statistical analyses of the diversity of good types of burials and tombs size, turquoise objects were found in high-status burials with more grave goods, showing that turquoise was linked to wealth and rank. Association rule analysis further reveals that the presence of turquoise significantly increased the co-occurrence probability of bone flutes and turtle shells, reinforcing its potential role in ritual or religious practices. Based on location, microwear analysis and ethnohistorical evidence, Jiahu turquoise served several purposes. Some pieces were used as personal ornaments such as earrings or pendants, showing taste and identity. Others were placed on

the eyes of the dead as symbolic jade mask, perhaps to connect the afterlife. Notably, thousands of turquoise beads scattered across the body from 10 tombs may have been part of a shamanic garment, buried as burial clothing. Consequently, Jiahu turquoise is a material and ideological medium connecting religion, power, and social identity, offering a fresh perspective for exploring the interaction between material and spiritual spheres in early Chinese civilization.

## 255. Connecting demographic agent-based models to skeletal data: the case of the rural Roman cemetery at Tiel-Passewaaij

*Laura van der Knaap (Vrije Universiteit Amsterdam)*

*Philip Verhagen (Vrije Universiteit Amsterdam)*

*Mark Groenhuijzen (Vrije Universiteit Amsterdam)*

### Introduction

Cemetery populations offer valuable insight into living populations, but undeniably, are “sampled at one particular time: at death” (Boldsen, Milner, and Ousley 2022, 121). To deal with this, paleodemographers have employed various methods, including modelling approaches. However, most models in paleodemography are deterministic and assume population stationarity or stability; this latter assumption, though unrealistic, ensures tractability.

A promising alternative, Agent-based modelling (ABM) is a popular bottom-up simulation method in archaeology, but it is only scarcely applied to cemetery data. ABM models a system according to its individual components, agents. ABM is stochastic and does not suffer from problems of tractability. It can examine the impact of varied social and environmental processes on the cemetery record.

This study combines ABM, skeletal data, and other site data to gain insight into the (rural) population of the Dutch Roman limes. The ABM was

previously applied by Verhagen and colleagues (2019), but no comparison with the archaeological record was made. Simulated age-at-death distributions are compared with empirical data from the site Tiel-Passewaaij (Aarts and Heeren 2011) in order to judge the relative plausibility of each simulation scenario.

## Methods and materials

Tiel-Passewaaij is one of the most complete Roman-period excavations in the Dutch Limes region (Aarts and Heeren 2011). The data for this case study is from the ‘central’ Roman cemetery located between two settlements, and dated from the mid first to the mid/late third century CE. The age-at-death distributions included 204 identified individuals, retrieved from 189 cremations.

The ABM used is the Batavian Demography and Army Recruitment (Verhagen 2019) agent-based model. The model includes agents who age, marry, reproduce, and die. Mortality is based on life tables. Fertility is age-specific and constrained by marital status. The ABM model was extended so that it generates a cemetery record.

Because very little is certain regarding mortality, fertility, and nuptiality in this region, a total of 9 scenarios were explored, using three model life tables and three marriage strategies. After a burn-in period of 50 years, every scenario is run for 210 years/ticks – the duration of cemetery use – or until the population has increased by a thousandfold ( $> 200,000$ ). Every simulation scenario is repeated 100 times.

Each simulation scenario was first analysed for population growth, size, and age-at-death distribution through visual comparison. Secondly, age-at-death ratios were used to quantify the differences between the simulation and archaeological data. Age-at-death ratios capture the ratio of specific population segments compared to others. Three ratios were used: the D5-14/D20+, the D15-29/D20+, and the D30+/D20+ ratio. A Ddiff measure was formulated based on these ratios to judge the overall match between the simulated and empirical distributions.

## Results

Depending on the scenario, annual growth percentages range from 0.6% to 4.3% per year, resulting in widely diverging final population sizes. When population sizes are relatively small (500 to 2000 individuals), growth percentages remain somewhat volatile, even after 200 years.

In terms of age-at-distribution, all simulation scenarios display a classic U-shape where age-class 0-5 makes up more than half of the distribution. However, smaller populations show a larger diversity in age-at-death distributions and living population structures.

All simulated distributions diverge from the empirical data. Notably, they underestimate the number of 0-5 and 30-40 year olds. However, the age-at-death ratios and Ddiff value indicate that the scenario with relatively low fertility and high mortality matches the empirical data best. The high fertility, low mortality scenarios perform the least well.

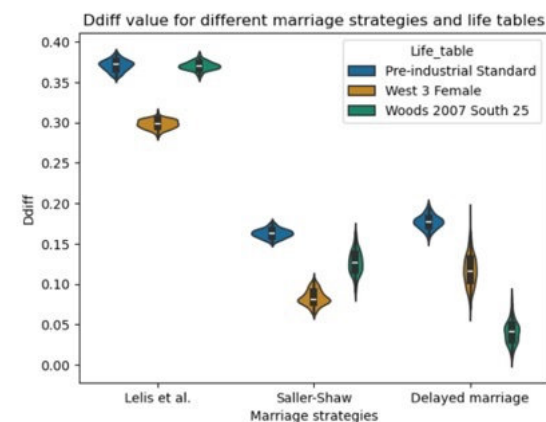


Figure 1: Ddiff for all nine scenarios; the lower the value, the better the match.

## Discussion

This analysis confirms previous conclusions (Verhagen 2019) that slight changes in fertility (marriage strategies) and mortality can significantly

impact dynamics in the long term. In terms of ABM enabling the comparison of different scenarios, the best matching runs imply an average growth rate of 0.6%, with short-term fluctuations between -0.6 and 2.0%. Generally, the growth rate for the pre-modern period is assumed to be no more than 0.2% (Verhagen 2019). However, there is a significant growth in settlements in the region in this period (Verhagen, Joyce, and Groenhuijzen 2016), and local communities experience more drastic periods of growth and decline than global averages might suggest (Boldsen, Milner, and Ousley 2022, 23). Some mismatches may be due to preservation, recovery, and age estimation biases of the empirical data. However, it is also possible we are missing an additional process, such as migration, that could boost the proportion of specific age classes.

This ABM does not incorporate assumptions of population stationarity or stability. Both growth rates and population structures show a greater diversity for smaller populations, and never reach an equilibrium. Nevertheless, it is these scenarios that best match the data: this shows that ABM has great potential for examining populations' non-stability as resulting from a wide range of (social) processes and general stochasticity. An important limitation is that certain scenarios with vastly different growth rates show relatively similar age-at-death distributions; this points to the challenge of equifinality and necessarily makes model validation a work in progress.

## Conclusion

This study sheds light on the complex interplay between fertility, mortality, and nuptiality that generates age-at-death distributions. The strength of ABM is that it can investigate the impact of different social processes on different scales and bridge the gap between theory and data. The fact that ABM does not shy away from heterogeneity and stochasticity helps highlight areas of equifinality and enables us to judge the relative plausibility of various scenarios.

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## 267. Social network analysis for refining the dating of individuals from Old Kingdom Egypt: A case study of the family tree of High Priests of Ptah

*Marek Bukáček (Charles University in Prague)*

*Veronika Dulíková (Charles University in Prague)*

For individuals living during Old Kingdom Egypt (c. 2180–2700 BCE), we do not usually have evidence of dates of birth and death, as is common in modern times. Only a few individuals are mentioned in connection with a ruler or a cattle census date. In view of the paucity of data for absolute chronology in the Old Kingdom, the dating of most individuals, their monuments and artefacts is still based primarily on relative chronology. This approach frequently involves the amalgamation of references to kings with dating according to various criteria, including the typology of scenes in tombs (Harpur, Linacre College, Oxford 2006), specific iconographic features (Cherpion), false door typology (Strudwick, Brovarski, Swinton, Roeten), title sequences

(Baer), etc. The present paper uses social network analysis applied to a large digital corpus to refine the relative chronology, as illustrated by the family tree of the High Priests of Ptah.

The Egyptological MaatBase database used for refining the dating Using our extensive MaatBase database containing data on more than 9,000 Old Kingdom individuals, their titles, family relations and burial places, we can build extensive family trees and networks of contemporaries. Each record about an individual contains information relating to the owner of the tomb/monument: site, tomb code, provenance, dynasty (or part of a dynasty), and king (or range of kings' reigns). If the ruler(s) under whom the person lived is not known, the dating is added based on the criteria mentioned in the introduction.

The limitations of family pedigrees proposed by Bierbrier (2006) in relation to ancient Egyptian chronology research can be significantly reduced by combining our comprehensive database with the SNA method.

#### Chronology refining steps

Before the refining the chronology, we compiled a dating dictionary, i.e. the table that converts dynasties, kings and other verbal information into numerical intervals. Furthermore, we have arranged these dating categories in a hierarchical structure based on the level of generality that should be applied during the aggregation step.

Subsequently, our approach uses the “middle of productive age” as the baseline for dating an individual. As the tombs of the elite were usually built during their lifetime, these monuments reflect the productive age rather than the date of death. While the middle of productive age is rather an approximation than exact milestone, this concept is useful for improving the process.

In addition to family members, many other people were often depicted in the tombs. Therefore, the date of a specific tomb may be assigned to numerous individuals related to the tomb owner. The known family relations of the tomb owner are applied in this approach to shift the dating of his family

members by generation difference(s). Individuals with no family relationship to the tomb owner are considered his contemporaries and their dating is not shifted. At this point, when verbal dating information is converted to a numerical interval and adjusted with respect to family relation, we have to handle the aggregation of multiple dating intervals referring to the same person. Here, the level of generality plays its role: Records containing significantly more general information (i.e., if there are multiple entries for a given person, the entry relating to the reign of the king takes precedence over that referring to the dynasty or part of a dynasty) are eliminated (and flagged for manual validation) and the remaining records are merged into one interval, which expresses the estimate of the midpoint of production age.

Finally, the family trees are used to narrow the dating intervals of related individuals. Even with expected differences in age among siblings, husbands and wives or other family members, there are multiple natural rules. The algorithm would e.g. adjust the dating of the children to be younger than their parents.

#### Social networks

In order to visualize and analyze the MaatBase, we shape the data into a multi-layer network, where people, titles and tombs are considered nodes and the various links between them are represented by edges. The positions of the nodes in such graphs are generated with respect to the closeness, reflecting chronology within the family. The shape, size and color of nodes are based on selected node features and depend on the purpose of the chart.

#### Results

Family members are represented by circles of sizes depending on the number of titles held by the given person, with the outer color defined by sex, yellow highlight referring to the holding the title High Priest of Ptah and inner red circle indicating royal family membership. Edges between people refer to recognized family relations (a thick line illustrates parent–child relations and marriage, a light line refers to siblings, a dashed line refers to uncertainty). The y-coordinate is derived from the generation within the family,

## Discussion

## References

doi: [https://doi.org/10.1163/9789047404002\\_006](https://doi.org/10.1163/9789047404002_006)

Maat-base: Database of proper names, titles and family relations of more than 9,000 Old Kingdom officials. The database has been developed by Veronika Dulíková. The online version of the database is currently undergoing preparation for launch, scheduled to occur in the coming months.

Laura Elmer (Universität Graz)

Edeltraud Aspöck (Universität Graz)

Ranging from a singular grave to almost half of the graves in a typical early medieval European cemetery have been reopened in the past. In some cases, graves have been disturbed before the deceased have even decomposed properly. Many re-entries were connected with the removal of artefacts and a synthesis of research on western and northern European cemeteries has recently led to the formulation of the hypothesis that the removal of artefacts may have been related to mortuary practices (Klevnäs et al 2021). The current project widens investigations and based on archaeological and historical sources it set out to investigate all types of human interactions with the dead in early medieval central and eastern Europe from the 5th to 8th

centuries CE. One main focus of the project is to examine the phenomenon of grave re-entries in the cemeteries of the period. Understanding the motivations and processes behind these re-entries is crucial for interpreting the complex relationships between the living and the dead during this period.

In an inhumation grave the fresh corpse is deposited in a grave cut in the ground. In an early medieval inhumation grave, the corpse was commonly buried in an organic container. After burial, natural processes such as the decay and decomposition of the corpse and the breakdown of the container and other organic structures took place which greatly changed the appearance of materials in the grave and, over years, decades, centuries and millennia formed the evidence that archaeologists would find (although most changes would take place in the years following burial). In addition to these natural formation processes, human activities may contribute to the formation of a mortuary deposit (or its taphonomy). If a grave was reopened soon after burial, human interference occurred whilst these natural processes were still ongoing. The traces of human activities in a grave after burial have therefore to be understood in the context of the natural processes that take place in the grave. The spatial distribution of human remains, artefacts, biological remains and other features can provide valuable insights into burial practices, taphonomic processes and the motivations behind grave re-entries. However, traditional methods of documentation often fail to capture the complexity of these contexts.

This project seeks to address this issue among other things, by leveraging 3D GIS to create detailed models of reopened graves, integrate bioarchaeological, environmental and geoarchaeological data and analyse spatial patterns. This research is part of the current project approach to overcome the deficits of available documentation from reopened ('disturbed') inhumation graves from previous excavations. High-resolution models of a small number of reopened inhumation graves serve as a basis for 3D reconstructions to create detailed reconstructions of the human activities in the graves, that will provide explicit information about what was done and allow evidence-based interpretation (Aspöck 2018). These models will inform the analysis and interpretation of graves with less detailed records available.

The 7th-8th c. CE Avar cemetery of Achau is located in Lower Austria and around 200 graves are known through geophysical survey. From 2024 to 2025 the project team excavated three inhumation graves (a child grave, an adult grave and a reopened adult grave) using the micro-archaeological protocol which enables an unprecedented level of detail to be achieved. The protocol includes single-finds recording (each find of 1cm or larger) with a tachymetre; image acquisition for image-based-modelling; flotation of sediments; soil sampling, including undisturbed soil samples for soil micromorphology; application of the project's archaeothanatological recording protocol adapted for reopened inhumation graves. The meticulous excavation and documentation provide the basis for a wide range of post-excavation analyses, which are valuable tools for reconstructing both natural and taphonomic processes involved in the formation of the graves.

In this paper, we will present our ongoing research using 3D GIS for the integration and (virtual) taphonomic analysis (Wilkinson-Dell'Unto 2015) of multi-disciplinary data resulting from our high-resolution excavations at Achau. The methodology employs photogrammetric techniques, particularly "Structure from Motion" to generate detailed 3D-Models of burial contexts directly on site. These models will be integrated with a database containing interdisciplinary excavation and post-excavation data to enable complex spatial analyses of taphonomic processes within a 3D GIS environment. The combined dataset will include spatial information on human remains, grave goods and structural features alongside specialist results from osteological, botanical and geochemical studies. Using a 3D GIS facilitates the visualisation and interpretation of spatial relationships, for example the distribution of burnt and unburnt biological remains, the positioning of grave goods and traces of post depositional disturbances.

The presentation will highlight the methodological challenges encountered during the creation and integration of 3D GIS models, including issues related to data collection and processing. It will also discuss the value of 3D GIS for mortuary archaeology, focusing on how this approach improves our understanding of burial contexts compared to traditional methods.



By presenting preliminary results from the case studies, this study demonstrates the transformative potential of 3D GIS for mortuary archaeology. The ability to integrate high-resolution 3D models with bioarchaeological data provides new insights into burial practices, taphonomic processes and the interactions between the living and the dead. This approach not only enhances our understanding of reopened graves but also offers a framework for applying 3D GIS to other complex archaeological contexts.

## 422. Modelling burial site distribution: A Machine Learning approach to funerary landscapes in Prehistoric Menorca

*Sonia Carbonell Pastor (Barcelona Supercomputing Center)*

*Hèctor A. Orengo (Barcelona Supercomputing Center)*

### Introduction

The funerary materiality of the island of Menorca stands out for its notable formal and spatial diversity. From the earliest tombs, dated to the second millennium BCE, through to the Roman conquest of the Balearic Islands in 123 BCE, multiple social transformations succeeded one another, which are reflected in the funerary practices and architectures of the communities that inhabited this territory (Guerrero et al., 2006; Lull et al., 2013; De Cet, 2017). Despite the knowledge already available on numerous funerary monuments, many remain concealed beneath vegetation cover. Archaeological survey campaigns have also been constrained by the regime of private land ownership: there have been few occasions on which the Consell Insular de Menorca has acquired archaeological plots to integrate them into the public heritage. This situation directly affects the conservation of the assets, especially when they are located on agricultural estates where farming tasks involve clearing stones from the fields, thereby increasing the risk of dismantling prehistoric structures. In other cases, these spaces have been reused to the point of altering their original morphology, as is the case with numerous burial caves, natural or artificial.

Considering this scenario, proactive heritage management by public authorities is essential. Nevertheless, any conservation intervention must first be preceded by the location, inventorying, and cataloguing of the assets, so that action can be taken where their state of preservation demands it.

This study proposes a predictive model to identify areas with potential for the presence of funerary monuments corresponding to the Late Bronze Age (Naviform–Talayotic in the local chronology) and the Iron Age (Talayotic–Post-Talayotic in the local chronology). The principal architectural expressions of these periods are, on the one hand, burial navetas (Gornés, 2016) and natural caves, and, on the other, artificial caves (rock-cut tombs) (Gornés et al., 1992; Gornés, 1996; Carbonell, 2025). Predictive models in archaeology make it possible to estimate areas with a higher probability of containing sites by integrating known variables, such as environmental data and spatial patterns identified in previous studies (Kamermans, 2006, 2010; Verhagen & Whitley, 2020).

The specific aims are: (1) to identify areas likely to contain funerary monuments according to their chronological attribution; (2) to recognise possible patterns in the spatial organisation of the funerary landscape for the Bronze Age and the Iron Age in Menorca; and (3) to explore the limits and potential of different methodological approaches for the generation of predictive models, comparing traditional deductive strategies with an inductive one based on Machine Learning (ML) algorithms.

### Methods and materials

This work is addressed through two complementary methodological approaches:

- (1) an inductive approach, based on Machine Learning algorithms.
- (2) a deductive approach, supported by rule sets and statistical patterns derived from previous studies.

To this end, we use a suite of variables distinguished as dependent and independent.

Dependent variables

Funerary sites serve as the response/target variable, differentiated into two layers according to typology:

- Navetes (Bronze Age tombs): points were sourced from the IDE Menorca spatial database (17 points)
- Artificial caves (Iron Age rock-cut tombs): points were obtained from field prospection and recorded with a Garmin eTrex 30 GPS (270)

Independent variables

We primarily integrate environmental and spatial-position variables:

- Altitude (DTM at 5 m resolution).
- Relative altitude
- Slope
- Orientation
- Temperature (including wind chill)
- Wind
- Pluviosity
- Cost/friction surface calculated using Tobler's function
- Geology.
- Soil type
- Topographic Position Index (TPI)
- Hydrology as barriers (Flow Accumulation, Flow Direction, and classification following Strahler's rule).
- Proximity to water sources.
- Seasonal variability proxies.
- Visibility Index.
- Closeness to communication corridors.

These variables will support predictive models capable of estimating zones with a greater likelihood of hosting new funerary sites.

Results

Initial tests confirm a higher reliability of ML-based approaches, which can meaningfully integrate a large number of variables and then weight them according to their statistical significance.

Discussion

Even though ML-based approaches have been considered as black boxes, shallow models allow the exploration of and hierarchisation of variables. They also present an important advantage respect to traditional rule-based approaches, in which the archaeologists select those variables they consider important and the weight of these variables: ML can ingest a large quantity of seemingly unimportant variables and then develop statistically significant weights, overcoming subjective bias in the process.

Although shallow ML approaches do not require as much training data as deep learning, they still require significant amounts for both training, validation and testing of the algorithm. These data, its quantity, quality and explanatory power, holds the key for the method selection and the interpretation of the results.

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### 435. The Neural Afterlife: Machine Learning Approaches to Reconstructing Roman Period Germanic Societies from Funerary Data

*Marek Vlach (Czech Academy of Sciences)*

*Balázs Komoróczy (Czech Academy of Sciences)*

*Petra Dragonidesová (Czech Academy of Sciences)*

The Germanic societies of the Roman Period, residing within an extensive geographical domain of continental Europe to the north of the Danube and

east of the Rhine, commonly referred to as Barbaricum, provide a rich archaeological record of the multifaceted cultural, social, demographic, and geopolitical contexts of Iron Age societies. Within this domain, the Suebian cultural environment represents a distinctive entity encompassing various subgroups, perceived by Roman historiography as ‘tribes’. Namely, the Marcomanni and Quadi also settled the low-lying parts of the present-day Bohemia, Moravia, Lower Austria, and SW Slovakia. Despite variations in material culture manifestations, these regions exhibit distinctive mutual resemblances. Within this environment, particularly the funerary record has always played a key role in research questions addressing social structure and stratification, whereas this specific segment of archaeological data contains a substantial abundance and the highest variability of available material culture. Thus, the aim is to address this research domain by applying advanced computational tools and techniques within the categories of neural networks and machine learning, allowing further conceptualisation with the social anthropological models.

## S21: Computational Approaches to Archaeology in Latin America and the Caribbean: Building Regional Dialogues

*Sebastian Fajardo Bernal*, Leiden University

*Cristian Gonzalez Rodriguez*, University College London

*Yoly Velandria*, Archaeological and Historical Conservancy, Inc.

*Daniel Sanchez-Gomez*, University of Lisbon

**Location:** Franz König Saal

**Session Format:** Standard

The newly created CAA Latin America and Caribbean Chapter provides a platform to connect the region's expanding network of researchers and practitioners applying computational approaches in archaeology and heritage. Across the region, there is an active and diverse community working on areas such as 3D reconstruction, digital heritage management, predictive modelling, GIS-based spatial analysis, remote sensing, archaeometry, human-environment modelling, and AI-assisted object reconstruction. These initiatives—developed in countries from the Andes to the Caribbean—often operate independently and face shared challenges related to accessibility, infrastructure, training, and collaboration.

This session seeks to bring these groups together to strengthen research networks that address local contexts, knowledge systems, and specific regional challenges. We invite contributions on computational archaeology in all its forms, including spatial analysis, predictive modelling, network and agent-based modelling, remote sensing, digital documentation, 3D visualisation, and machine learning. Case studies, methodological developments, and theoretical reflections are welcome, whether based on fieldwork, historical datasets, or experimental projects.

The session will highlight the conditions shaping computational research in Latin America and the Caribbean. These include limited digital autonomy, fragmented communication channels, and barriers to research mobility that restrict collaboration across countries and institutions. At the same time, the region offers fertile ground for innovation, drawing on its rich ecological and cultural diversity and supported by a vibrant network of researchers, Indigenous communities, and other local stakeholders eager to amplify their voices in global dialogues. By confronting these challenges while building on the region's strengths, the session aims to foster a more inclusive and diverse computational archaeology. It seeks to lay the groundwork for systematic and rigorous practice in the region, promoting sustained collaborations, shared digital resources, and long-term capacity building.

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|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>11:00 – 11:20</b> | 27. Evaluating the Limits of Denoising Autoencoders for the Restoration of Mayan Hieroglyphic Imagery<br><i>Valeria Duran Rubio (Instituto Tecnológico Autónomo de México); Edgar Roman-Rangel (Instituto Tecnológico Autónomo de México)</i>                                                                                             |
| <b>11:20 – 11:40</b> | 50. Simulating Late Muisca Geopolitical Patterns<br><i>Eduardo Herrera Malatesta (Leiden University); Andrew Bevan (University College London); Pedro M. Argüello García (Escuela de Ciencias Sociales, Universidad Pedagógica y Tecnológica de Colombia); Aranka Kriekaart (Leiden University); Alexander Geurds (Leiden University)</i> |
| <b>11:40 – 12:00</b> | 67. Population and Empire: A New Regional Demographic Model for the Purépecha Imperial Heartland using LiDAR and Settlement Scaling Theory<br><i>Benjamin Shirey (Colorado State University)</i>                                                                                                                                          |
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|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>12:00 – 12:20</b> | 80. From GIS to Archaeology: Archaeological Sensitivity Modeling for Taltal (Antofagasta, Chile)<br><i>Margarita Romero (UAB); Juan Antonio Barceló (UAB); Ermengol Gassiot (UAB)</i>                                                          |
| <b>12:20 – 12:40</b> | 268. Challenges and opportunities for developing artificial intelligence projects in Mexican archaeological institutions<br><i>Diego Jimenez-Badillo (National Institute of Anthropology and History of Mexico)</i>                            |
| <b>12:40 – 13:00</b> | 274. Techno-typological pottery clusters in the Istmo Panama area<br><i>Daniel Sánchez Gómez (Universidade de Lisboa (UNI-ARQ)); Carlos Gómez (Cobre Panamá); Alejandra Quintero-Rúa (Cobre Panamá); Sebastián Fajardo (Leiden University)</i> |
| <b>13:00 – 14:00</b> | Lunch break                                                                                                                                                                                                                                    |
| <b>14:00 – 14:20</b> | 313. Investigating the legacy effects of colonial-era Indigenous resistance on recent deforestation in the southern Atlantic Forest<br><i>Barney Harris (Bournemouth University); Freg Stokes (Max Planck Institute of Geoanthropology)</i>    |
| <b>14:20 – 14:40</b> | 352. Chullpas in Series: A 3D-Based Morphometric and Spatial Workflow for Andean Funerary Architecture<br><i>Cristian Gonzalez Rodriguez (University College London); Marta Crespo Fernandez (Incipit-CSIC)</i>                                |

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|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:40 – 15:00</b> | 356. Question-Driven Collaboration: Federated Virtual Survey with the Geospatial Platform for Andean History, Culture, and Archaeology (GeoPACHA)<br><i>Nathaniel VanValkenburgh (Brown University); Steven Wernke*; James Zimmer-Dauphinee*; Yuankai Huo*; Junlin Guo*; Matthew Ballance (Brown University); Jacob Bongers (University of Sydney); José Capriles Flores (Pennsylvania State University); Cristian González Rodríguez (University College London); Ericka Guerra Santander (Universidad Nacional San Agustín); Frances Hayashida (University of New Mexico); Manuel Mamani Calloapaza**; Giancarlo Marccone (Universidad de Ingeniería y Tecnología); Raquel Mejía Aranguren**; Pablo Mendez-Quiroz Aranda (Universidad de Chile); Gabriela Oré Menéndez (University of Nevada); Jo Osborn (Texas A&amp;M); Alexis Reátegui Díaz**; Kevin Ricci Jara (Independent Scholar); Grecia Roque Ortega**; Jason Toohey (University of Wyoming); Anthony Villar Quintana**</i><br><br><i>* Vanderbilt University<br/>** Independent Scholar</i> |
| <b>15:00 – 15:20</b> | 377. Tracing empires: settlement dynamics in the Yau-tepec valley (Mexico) between 1500 BC and 1520 AD<br><i>Giacomo Bilotti*; Natália Fedorová*; Iza Romanowska*; Michael Smith (Arizona State University)</i><br><br><i>* Aarhus University</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| <b>15:20 – 15:40</b> | 408. Memory and Control: Digital mortuary landscapes from Wari to Colonial Peru in the Huarmey & Culebras valleys                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |

Miłosz Giersz\*, Patrycja Prządka-Giersz\*, Wiesław Więckowski\*; Roberto Pimentel Nita\*; Maciej Kałaska\*; Jakub Stępnik\*; Jędrzej Szymanek\*; Izabela Kurjan\*; Julia Chyla\*

\* University of Warsaw)

**15:40 – 16:00** 450. Modeling hunter-gatherer-fisher communities in the South Pacific: A high-resolution spatial approach to studying coastal settlements in the Atacama Desert

*Pablo Mendez-Quiros\*; Cristian González (University College of London); Estefanía Vidal (Universidades Alberto Hurtado); Mauricio Uribe (Universidad de Chile); Francisca Santana (Pontificia Universidad Católica de Chile); Vesna Obilinovic (Universidad Arturo Prat); Claudio Wande\*; Diego Mayorga (Pontificia Universidad Católica de Chile); Montserrat Javalquinto\*; Camila Ramírez\**

\* Universidad de Chile

**16:00 – 16:20** 454. Applying Gaussian Splatting at a Coastal Maya Site El Meco

*Ashuni Emmanuel Romero Butróni (Centro INAH Quintana Roo); Nelda Issa Marengo Camach (University of New Mexico)*

**16:20 – 16:30** Discussion

## 27. Evaluating the Limits of Denoising Autoencoders for the Restoration of Mayan Hieroglyphic Imagery

*Valeria Duran Rubio (Instituto Tecnológico Autónomo de México)*

*Edgar Roman-Rangel (Instituto Tecnológico Autónomo de México)*

The study of ancient hieroglyphic inscriptions carved in stone represents a fundamental challenge in archaeology, as it is crucial for understanding the languages and symbolic systems of ancient civilizations. However, these artifacts often suffer from physical deterioration, environmental exposure, and erosion, which complicate their documentation and analysis (Doehne and Price 2010; Oguchi 2021). Traditional restoration and recording methods are not only labor-intensive and time-consuming but also carry risks of physical damage to the materials (National Park Service 2022b).

In this context, the integration of artificial intelligence (AI) and deep learning techniques offers a promising framework for assessing the limits of digital restoration in cultural heritage, one example of this is the Mayan inscriptions. Concretely, this work exploits the deep learning architecture known as Convolutional Autoencoder (CAE). Rather than focusing solely on image reconstruction, this research aims to determine to what extent and under what types of noise degradation the CAEs can effectively recover information in Mayan hieroglyphic images. These architectures learn latent representations that facilitate partial noise removal and structural preservation without manual annotation, enabling a systematic evaluation of model resilience across varying noise intensities and patterns. By identifying the thresholds beyond which restoration becomes unreliable, this study contributes to both archaeological practice and computational imaging, offering a replicable approach to quantify the robustness of deep learning models for heritage data.

The dataset used in this study comprises 1,280 grayscale images of Mayan glyphs, each corresponding to distinct syllables. The images were preprocessed through several steps: normalization, resizing to 64×128 pixels, and conversion to single-channel grayscale format to ensure uniform input dimensions. All images were binarized, reducing each pixel to 0 or 1 to ensure



compatibility with the binary cross-entropy loss function and to simplify computation while preserving key structural details.

To assess model robustness, two types of synthetic noise were applied: structured noise, introduced through circular occlusions of varying radius and frequencies to simulate localized deterioration; and Gaussian noise, added as pixel-level perturbations of increasing intensity to represent diffuse degradation. All experiments were implemented in Python using TensorFlow, NumPy, and scikit-image.

A series of convolutional autoencoders (CAEs) was designed and trained to evaluate performance under the different noise scenarios. Each model followed a symmetrical encoder–decoder architecture that compressed and reconstructed images through successive convolutional and upsampling layers. The encoder progressively reduced spatial resolution while increasing feature depth, and the decoder inverted this process to recover the original structure. Hidden layers used ReLU activations, with a sigmoid function in the output layer to match the normalized pixel range. Training was optimized with Adam and the binary cross-entropy loss function.

Among several configurations, the best-performing model combined binarized inputs with stratified data division, achieving high reconstruction fidelity and stable generalization. This configuration was later extended into a denoising autoencoder, enabling systematic analysis of how different noise types and intensities affect the model’s capacity to recover visual information. This best-performing variant employed two convolutional blocks in the encoder (32 and 64 filters) and decoder, with Dropout layers (0.3) to mitigate overfitting. The model balanced representational power and computational efficiency, totaling approximately 185,000 trainable parameters, and was trained using mean squared error (MSE) as the loss function.

Model performance was assessed through four metrics: MAE (Mean Absolute Error), PSNR (Peak Signal-to-Noise Ratio), SSIM (Structural Similarity Index), and loss convergence.

Among non-denoising models, our best model achieved MAE = 0.002, PSNR = 34.89 dB, and SSIM = 0.996, outperforming all other configurations. This

demonstrates that combining binarization with class-stratified splitting enables high-fidelity reconstruction and improved generalization.

For denoising tasks, under structured noise, errors increased proportionally with the number and size of occlusion patches. The best-performing denoising model achieved MAE = 0.0849 with minor degradation at high noise levels. Under Gaussian noise, the model achieved MAE = 0.044 for low-intensity noise (factor 0.2), and 0.070 for high-intensity noise (0.6), maintaining SSIM values above 0.81, indicating strong structural preservation.

These results reveal that the model handles diffuse Gaussian noise more effectively than localized occlusions, as the latter involve irreversible information loss.

Visual comparisons confirm that the autoencoder can reconstruct clean glyph shapes even when significant noise is present. In structured-noise tests, the model successfully removed most occlusions but produced slight blurring or gray patches where information was missing—an expected consequence of MSE minimization. Applying post-reconstruction binarization restored sharper contours and improved interpretability, aligning the outputs more closely with the original black-and-white glyph aesthetic.

This research demonstrates that convolutional autoencoders can successfully restore archaeological imagery within defined limits of noise intensity and structure, thereby establishing empirical thresholds for the effectiveness and breakdown of denoising performance.

The findings reveal several key relationships that clarify the model’s behavior under different conditions. First, noise type sensitivity plays a crucial role: the autoencoder performs more effectively with global, diffuse perturbations such as Gaussian noise than with localized structural damage, where the complete loss of pixel information restricts its ability to reconstruct the original image. Second, there is a positive correlation between glyph complexity and reconstruction error, indicating that images with denser or more intricate black stroke patterns tend to yield higher reconstruction errors, particularly when affected by structured noise. Finally, regarding model compactness and accuracy, results show that an intermediate-sized architecture offers the best balance between computational efficiency and

reconstruction quality, suggesting that increasing network depth does not necessarily produce proportional improvements in performance.

Beyond image restoration, these results have broader implications for cultural heritage digitization. They demonstrate that relatively lightweight deep learning architectures can provide archaeologists with non-invasive, replicable methods for visual analysis, classification, and digital archiving of ancient scripts.

This study demonstrates the feasibility and effectiveness of convolutional denoising autoencoders in reconstructing and restoring degraded images of Mayan hieroglyphs. Through systematic experimentation with multiple architectures, data configurations, and noise scenarios, the research identifies optimal design choices for balancing accuracy and efficiency in archaeological imaging applications.

While promising, the models still face challenges with localized data loss and fine-detail recovery. Future work should explore variational autoencoders (VAEs) and other generative models, which have shown potential in similar restoration contexts (Scardozzi et al. 2022; Gao, Hui, and Li 2024). Integrating these approaches could enhance the model's ability to regenerate missing information rather than merely smoothing over damaged regions.

Ultimately, this work positions deep learning as a practical and ethical tool for digital heritage preservation, establishing measurable thresholds for the effectiveness and limitations of denoising models and bridging computational imaging with archaeological research through a systematic understanding of how far restoration remains reliable under different noise conditions.

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## 50. Simulating Late Muisca Geopolitical Patterns

*Eduardo Herrera Malatesta (Leiden University)*

*Andrew Bevan (University College London)*

*Pedro M. Argüello García (Escuela de Ciencias Sociales, Universidad Pedagógica y Tecnológica de Colombia)*

*Aranka Kriekaart (Leiden University)*

*Alexander Geurds (Leiden University)*

This paper explores how computational modelling and simulation can serve as critical tools to interrogate and reframe colonial legacies embedded in traditional narratives. Focusing on the Late Muisca (~1000-1550 CE) territory, located in the Colombian Central Andes, we develop a quantitative framework to model patterns of interaction and political centrality among late pre-Hispanic settlements. By integrating spatial interaction models (SIMs) with geospatial and historical datasets, we investigate how political cohesion and movement dynamics might have structured the territorial organisation of Late Muisca communities before and during early colonial encounters. Our approach builds on the foundational work of Wilson (1971) and Bevan and Wilson (2013), who formalised SIMs as tools to infer flows of interaction between sites based on costs, opportunities, and constraints. We adapt these models to account for non-linear relationships between geography, visibility, and social connectivity variables that are particularly relevant to highland societies characterized by dense settlement networks and heterogeneous topography. The analysis combines a series of relevant covariates with iterative simulations that test the sensitivity of interaction flows to variations in distance-decay and population parameters. The resulting matrices are validated

against ethnohistorical and archaeological data. Through the application of statistically robust spatial modelling, we successfully generated a set of simulated archaeological sites informed by significant correlations between known archaeological locations and key environmental covariates. A preliminary visual inspection revealed that these simulated sites reproduce spatial structures broadly consistent with those found in the empirical archaeological record. Moreover, the simulated distribution appeared to echo the general patterns described by early Spanish chroniclers, suggesting a meaningful convergence between modelled expectations and historical accounts.

Methodologically, this work contributes to the broader effort of embedding decolonial awareness into quantitative archaeology. It emphasises the need to treat models as heuristic and dialogical rather than deterministic, acknowledging that parameter choices, cost definitions, and validation criteria all encode specific epistemological assumptions. In doing so, the project aligns with current debates on the epistemic transparency and reflexivity of computational archaeology, proposing that modelling can become an arena for theoretical engagement rather than mere prediction (e.g., Fajardo & Argüello García, 2024). Ultimately, this study demonstrates that quantitative methods, when critically applied, can illuminate the social and political textures of past landscapes while simultaneously exposing the inherited colonial frames that have shaped archaeological interpretation. Computational archaeology thus emerges as both a technical and theoretical practice, one capable of reconciling formal modelling with plural, situated ways of knowing the past.

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## 67. Population and Empire: A New Regional Demographic Model for the Purépecha Imperial Heartland using LiDAR and Settlement Scaling Theory

*Benjamin Shirey (Colorado State University)*

### Introduction:

In this paper, I explore the role of demographic processes in the consolidation, administration, and collapse of the Purépecha Empire by investigating the demographic scale and spatial patterning of settlement in the Lake Pátzcuaro Basin (LPB), Michoacán, Mexico in the Late Postclassic Period (1350-1520 CE). The LPB formed the heartland of the Purépecha Empire in the Late Postclassic and was home to the imperial capital Tzintzuntzan and several other dense urban centers. In the last thirty years, researchers have discovered new settlements in this region, including the expansive urban zone of Angamuco, but published estimates for the size, distribution, and makeup of its population have not kept up with these discoveries. Here, I construct a new model using material evidence from recent LiDAR and pedestrian survey data and from mathematical patterns provided by Settlement Scaling Theory. Through this model, I critique the previous model presented by Gorenstein and Pollard (1983) and challenge their primate city concept of the LPB and the sociopolitical implications thereof. Based on the new model presented here, I propose that the demographic scale of urban settlement was much more extensive than accounted for previously, and that demographic processes such as immigration and settlement expansion

played a greater role in the processes of imperial consolidation administration, and collapse than previously thought.

#### Methods and Materials:

This project synthesizes precise settlement size and density data from recent LiDAR surveys with ground survey data and insights from Settlement Scaling Theory to produce a new regional demographic model. The LiDAR data, courtesy of Legados de la Resiliencia: La cuenca del Lago de Pátzcuaro Proyecto Arqueológico (Legacies of Resistance: The Lake Patzcuaro Basin

Archaeological Project, or LORE-LPB), covers the Angamuco malpaís on the eastern side of the basin and the Itzira malpaís on the western side of the basin. I derive a population estimate for the large city of Angamuco using the LiDAR coverage combined with pedestrian survey GIS data. Settlement Scaling Theory (SST), a body of research that has identified mathematically consistent patterns across cultural contexts in the ways quantifiable urban characteristics scale with population, provides a means for extrapolating this estimate into a model for the entire LPB. SST observes a sublinear relationship between settlement size and population and expresses this relationship with the formula " $A = aN^\alpha$ " in which  $A$  = area,  $N$  = population and  $a$  and  $\alpha$  are constants specific to a given settlement system. I use the Angamuco population estimate to derive a version of this formula specific the LPB. I apply this formula to all known Late Postclassic settlement sites in the LPB as described in published literature and in the INAH Sistema Único de Registro Público de Monumentos y Zonas Arqueológicas e Históricas (Single Public Registry System of Monuments and Archaeological and Historical Zones), thus generating a new regional demographic model.

#### Results:

For the city of Angamuco I estimate a Late Postclassic population of 23,600-31,000 people. For the entire LPB I estimate a Late Postclassic population of 147,800-200,200 people. This estimate is 117% larger than the previously available model (Gorenstein and Pollard 1983). The new model characterizes

the population distribution as dense and full throughout the LPB, a projection that is incompatible with the previous primate city pattern. Thus, the model shows that the LPB population existed on a much greater scale than previously imagined, clustered in a diverse array of highly developed urban settlements.

#### Discussion:

This new demographic model provides insights into Purépecha imperial origins, administration, and collapse. The model shows that the Purépecha Empire formed in a time of intense demographic concentration within the LPB and that demographic processes likely played a role in the formation of a new, complex, hierarchical form of social organization in the region. This model also shows that imperial administration and the maintenance of power in the LPB was not a simple task. The ruling class had to employ political and economic strategies to maintain control of this large population, including state control of resource redistribution, careful placement of administrative centers, and population centralization policies favoring the capital city of Tzintzuntzan. Finally, this new model illuminates the scale of the demographic collapse that drove the collapse of the Purépecha Empire. This model estimates that between 1520 and 1550 the LPB population fell by 68% due to the disease, conflict, and enslavement brought by Spanish Colonization

This analysis does not support the extreme primate city model proposed before but paints a much more complex picture. The basin had multiple large settlements, boasting major urban centers of 5,000 people or more across the basin including Tzintzuntzan, Angamuco, Pátzcuaro, Erongarícuaro, Ihuatzio, Pueblo Viejo, and the Itzira malpaís. It also contained a unique zone of continuous, multi-nucleated settlement spanning an area of approximately 26 km<sup>2</sup> on the Angamuco malpaís. This validates Fisher et al.'s (2017) contention that Purépecha urbanism was well developed before the foundation of the empire, consisting of a highly concentrated population atop and between the malpaíses.

This new model has important implications for all future Purépecha scholarship. The population of the LPB in the Late Postclassic was much larger and complex than previously thought, and as research continues, this will likely be shown to be true for regions across the indigenous Americas. This model also proves Settlement Scaling Theory's utility as a predictive rather than descriptive method. I hope this model will improve over time with expansion of LiDAR coverage and innovations in Settlement Scaling Theory.

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## 80. From GIS to Archaeology: Archaeological Sensitivity Modeling for Taltal (Antofagasta, Chile)

*Margarita Romero (UAB)*

*Juan Antonio Barceló (UAB)*

*Ermengol Gassiot (UAB)*

### Introduction

The integration of Geographic Information Systems (GIS) and statistical modeling in archaeology has enabled the development of predictive tools to estimate the archaeological potential of landscapes. These models are increasingly used in heritage management and research, particularly in areas with scarce or discontinuous material evidence.

Taltal, located in the Antofagasta Region, is characterized by an extreme desert environment with sparse vegetation, high thermal amplitudes, and low availability of surface water. Its geomorphology comprises a Coastal Cliff, a Coastal Range, the Intermediate Depression, and the Domeyko Precordillera. Paleoenvironmental conditions during the early Holocene, marked by greater humidity and higher biotic productivity, likely favored temporary human occupation of the area.

However, the archaeological record has been concentrated along the coastal strip, where evidence of fishing and gathering has been documented since the early 20th century. In contrast, the inland desert was traditionally viewed as a transit or lithic procurement zone, a hypothesis that this study aims to evaluate from a spatial and quantitative perspective (Salazar et al. 2015).

This study develops an archaeological sensitivity model for Taltal in northern Chile using the Maximum Entropy (MaxEnt) approach (Phillips et al. 2006). The primary objective is to identify environmental variables that influence the distribution of archaeological sites in the Intermediate Depression, an arid environment traditionally regarded as a lithic procurement zone for coastal hunter-gatherer groups during the Holocene (Salazar et al., 2015). The model aims to enhance understanding of human-environment

interactions in desert settings and provide a decision-support tool for archaeological prospection and cultural heritage management.

#### Methods and Materials

An inductive modeling approach was adopted using empirical data from 131 prehistoric archaeological sites compiled from Chile's Environmental Assessment System. Most sites correspond to lithic workshops and simple structures linked to the processing of siliceous materials. Additionally, 64 pseudo-absence points were defined in surveyed areas lacking prehistoric evidence. The environmental variables included were altitude and slope derived from ALOS PALSAR DEM (12.5 m resolution), distance to watercourses (national hydrographic dataset), lithostratigraphic units (Geological Map of Chile) and proximity to lithic procurement areas (Borie et al. 2023).

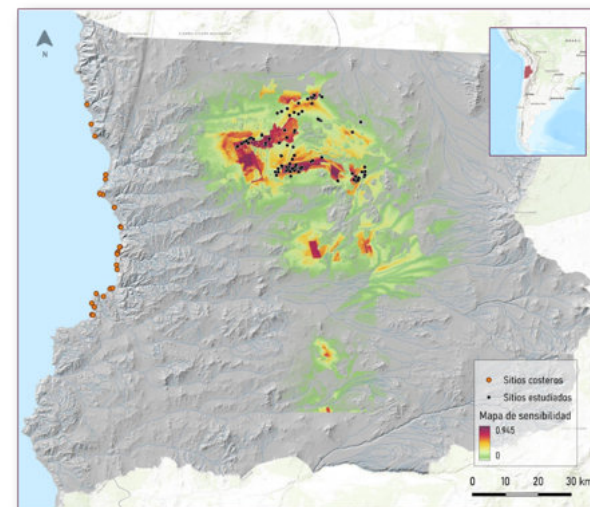
All layers were standardized to a uniform spatial resolution and projected in WGS84. Modeling was conducted using MaxEnt, testing different variable combinations and training/test splits (70/30). Model performance was assessed through AUC, gain, and threshold-based metrics, complemented by confusion matrix-derived indicators such as precision, recall, specificity, and F1-score.

#### Results

Among eight models tested, Model 2 performed best, achieving AUC > 0.9, 92% sensitivity, and F1-score = 0.81. The most influential variables were proximity to lithic procurement zones, distance to water sources, lithostratigraphic units, altitude and slope.

The resulting archaeological sensitivity map delineates areas of high probability of site occurrence, particularly in the Domeyko Range and transitional zones between the pampas and ancient riverbeds. These high-sensitivity areas correspond to known archaeological mobility corridors that link inland workshops with coastal camps.

Although specificity is low (0.33), the model minimizes false negatives, favoring overprediction as a preventive criterion for heritage protection and field prospection planning.



#### Discussion

The study demonstrates the applicability of MaxEnt models for predicting archaeological site distributions in arid landscapes with fragmented datasets. Water availability and access to lithic raw materials emerge as primary factors influencing site location, underscoring the integrated nature of coastal and inland occupation systems in Taltal.

Methodologically, combining archaeological datasets with remote sensing and probabilistic modeling offers a replicable framework for other arid zones. Complementary performance metrics beyond AUC provided a more comprehensive evaluation of predictive accuracy, confirming the model's robustness for research and management purposes.

Limitations include environmental homogeneity, lack of paleoclimatic variables, and manually defined pseudo-absences. Future research should integrate socio-cultural and paleoenvironmental variables and develop systematic "survey effort" layers to improve model reliability.

#### Conclusions



The sensitivity model reveals that hydrological and geological factors have a significant impact on the distribution of archaeological sites. Its high sensitivity (92%) highlights MaxEnt's potential for predictive archaeology and heritage management. By redefining the Intermediate Depression as an active resource and mobility space rather than a marginal zone, this research provides a quantitative foundation for future studies of prehistoric landscapes in the Atacama Desert.

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## 268. Challenges and opportunities for developing artificial intelligence projects in Mexican archaeological institutions

*Diego Jimenez-Badillo (National Institute of Anthropology and History of Mexico)*

Thanks to its rich historical legacy, Mexico has cultivated a robust tradition in the recovery and preservation of cultural heritage. Each year, hundreds of sites and architectural structures, along with thousands of artifacts, are incorporated into the nation's archaeological, historical, and artistic

collections. This ongoing expansion poses significant challenges for memory institutions—such as museums, archives, libraries, and research centers—which are tasked with cataloguing, analyzing, preserving, and sharing this heritage with diverse audiences.

As institutions worldwide have recognized, advanced computational methodologies—such as computer vision (CV), machine learning (ML), and artificial intelligence (AI) based on Large Language Models (LLM)—provide powerful tools for addressing complex challenges.

European research institutions, in particular, have developed a rich ecosystem for the development and application of methodologies that improve the analysis of Cultural Heritage. Part of such ecosystem are dedicated academic programs, scholarly journals, conferences—with CAA among the most important, and collaborative research networks. In contrast, Mexico continues to face significant structural and institutional challenges that impede the adoption of these technologies in cultural heritage research and practice (Galina-Russell, 2012, 2016; Priani Saiso, 2012). This paper addresses in particular three main challenges:

- A rigid legal framework for managing cultural heritage data

The management of cultural heritage data in Mexico is governed by a strict legal framework that designates such heritage as national property. The National Institute of Anthropology and History (INAH) holds exclusive authority over the documentation, preservation, and dissemination of cultural heritage. As a result, any data derived from heritage materials—such as photographs, 3D scans, historic documents, or field notes—may also fall under state jurisdiction. Current legislation significantly restricts the ability of private individuals or institutions from independently conducting research, documentation, or dissemination activities related to cultural heritage without prior authorization from INAH. This includes the use of such materials for educational or academic purposes. Researchers must obtain explicit permission to access, reproduce, or publish cultural heritage data, and are subject to legal and ethical review processes. This legal context presents significant challenges regarding data ownership, intellectual property rights, and the

public dissemination of cultural content. It also raises broader questions about access to knowledge, the role of independent research, and the balance between cultural preservation and academic freedom (Rios-Allier, 2020).

- Lack of Funding for Technological Infrastructure in Cultural Institutions

Austerity policies in the education and culture sectors have significantly hindered the implementation of technologies that require specialized equipment. At the National Institute of Anthropology and History (INAH), for example, strict administrative restrictions on the acquisition of computer equipment have made it difficult to establish specialized laboratories and research infrastructure. Consequently, researchers are often forced to seek external funding to carry out their work. However, this is particularly challenging given that there is only one public funding source for research in the country: the Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI), which provides support across all disciplines, including science, technology, and the humanities. One notorious consequence of the lack of funding for equipment is the scarcity of projects for digitizing public collections.

- Low Level of Digital Literacy Among Humanities Professionals

The legal and financial challenges faced by the Humanities in Mexico are further exacerbated by a limited level of digital literacy among professionals and students in the field. Many lack formal training in mathematics and computational modeling, which hinders the adoption of advanced tools such as artificial intelligence, machine learning, and Big Data analysis.

To foster effective collaboration with technology experts, cultural heritage institutions must recognize that these digital competencies are essential. This means not only raising awareness of their importance but also implementing accessible training programs tailored to the sector's specific needs. The situation is even more critical in marginalized communities, where access to technology and digital education remains limited. Addressing this gap

requires inclusive policies that promote digital equity and ensure that all Humanities professionals can fully participate in the technological transformation of the field.

During the presentation, some solutions will be proposed.

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## 274. Techno-typological pottery clusters in the Istmo Panama area

*Daniel Sánchez Gómez (Universidade de Lisboa (UNIARQ))*

*Carlos Gómez (Cobre Panamá)*

*Alejandra Quintero-Rúa (Cobre Panamá)*

*Sebastián Fajardo (Leiden University)*

The environmental particularities of the Panamanian Central Caribbean have historically restricted the development of a systematic archaeological research agenda, resulting in an area of immense cultural interest that is under-represented in the general context of Panamanian research. High rainfall, clayey soils of high acidity and impermeability, and steep terrain have a significant impact on the poor preservation of archaeological contexts and materials. In the particular case of ceramics, they contribute to severe erosion and fragmentation of the vessels, limiting the possibilities of typological identification.

In contrast to the Panamanian Pacific contexts such as Gran Coclé, where ceramics present a rich decoration associated with funerary contexts, which has been the object of exhaustive studies and has become a regional reference, Central Caribbean pottery were oriented towards utilitarian and domestic functions, with less decoratively prominent features despite the fact that uninterrupted occupation of the area by farming pottery groups has been documented for over 2000 years. Despite some efforts, limited research has prevented the establishment of a systematic ceramic classification in this area. Although some autochthonous styles have been identified, such as 'Limón' and 'Donoso' (Griggs, 2005), as well as more recent ones such as Cobre (AD 608-1460) and Dorado (AD 1260-1434) (Gómez et al., 2023), the available data is still insufficient for a precise categorisation.

Against this background, this work explores the utility of incorporating a computational workflow as an alternative to traditional methods of ceramic

analysis in Panamanian archaeology that overcomes the challenges derived from the severe erosion caused by environmental and taphonomic conditions and the sparse decoration of these pottery. The existence of a new large database with ca. 25k ceramic fragments recovered from the Mina de Cobre Panamá project (2019-2023), has allowed us to explore a data-driven approach to address some of the existing gaps and advance the understanding of the long-term historical processes of this interesting region.

### Methods:

We have implemented a workflow that combines statistical tests, unsupervised and supervised machine learning techniques to build a ceramic classification protocol which allows us to discover patterns in previously unknown data and move towards defining a formal typology for the region. After an exhaustive Exploratory Data Analysis aimed at obtaining a curated database, we have employed a clusterability analysis using a Dip test (Hartigan 1985) based on the pairwise Gower's distance matrix as it is the best candidate among similarity measures for dealing with mixed data datasets.

The next step has been to use a DBSCAN cluster analysis to find an optimal number of groups that represent the existing technological ceramic diversity. Next, several supervised classification algorithms will be compared and a complete workflow will be constructed that allows for the cultural association of new ceramic fragments.

The resulting clusters will be correlated with Bayesian analysis of ca. n=69 available C14 datings of ca. 80 archaeological sites, allowing us to take the first steps towards the modeling of complex social networks that will help us to reconstruct the social dynamics of the region, especially between [-300 BC and 1700 AD] when a dramatic population decline took place due to the establishment of a pacification campaign by the colonial authorities.

### Results

Preliminary results are quite promising and have allowed us to better understand the diversity and evolution of the pre-hispanic ceramic production in the central Caribbean Panama. The clusterability analysis has revealed a multimodal dataset and DBSCAN has confirmed the existence of four different

techno-typological groups that are currently being evaluated based on chrono-spatial data to assess their inter-settlement distribution. At the time of writing this proposal, the results of the cluster analysis are being verified archaeologically. Once validated, the various supervised algorithms will be trained to complete the workflow.

#### Discussion

The main objective of this work is to explore the applicability of a computational workflow for solving a common problem in archaeology, namely ceramic classification, by exploiting the availability of a large, unpublished dataset uncommon for the context of the Panama Central Caribbean.

The use of supervised and unsupervised approaches within the same framework is quite common, and clustering analyses have proven to be very useful for solving classification problems. What is not very common is the incorporation of a preliminary step that evaluates the clustering capacity of the data sets. It is well known that clustering algorithms tend to generate clusters regardless of the actual distribution of the data. Here we propose that it is essential to carry out a preliminary evaluation before any clustering analysis that leads to the construction of any typology.

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### 313. Investigating the legacy effects of colonial-era Indigenous resistance on recent deforestation in the southern Atlantic Forest

*Barney Harris (Bournemouth University)*

*Freg Stokes (Max Planck Institute of Geoanthropology)*

The Atlantic Forest extends from northeastern Brazil along the Atlantic coast and inland into northeastern Argentina and eastern Paraguay, encompassing 15 ecoregions that include tropical and subtropical rain forests, coastal forests, mangroves, and Araucaria moist forests. Ranking among the world's top biodiversity hotspots, the forest plays a vital role in climate regulation, with one hectare in the Upper Paraná ecoregion storing an average of 223.5 tons of carbon, and the Serra do Mar ecoregion holding between 320 and 460 tons per hectare, depending on elevation.

Once spanning more than 350 million acres, the Atlantic Forest has lost ~88% of its original vegetation to human activity, leaving it one of the most endangered biomes on the planet. Although much of this deforestation occurred over the last century, the process began en masse with the colonisation of the region by the Spanish and Portuguese during the 16th–19th centuries, with early colonial settlement patterns and key transport routes influencing the spatial distribution of deforestation in the region.

Recent studies have begun to recognise contemporary Indigenous territories as critical spaces for forest conservation, but less attention has been paid to the historical impacts of colonial-era Indigenous resistance on historic and present-day deforestation patterns. To address this gap, our research examines geolocated sites of historically documented Indigenous resistance (C16th-19th) and their effects on deforestation up to c. 1965 using an explanatory spatial Random Forest model.

We introduce distance from Indigenous resistance sites as a spatial predictor within our deforestation model, in combination with other environmental and anthropogenic predictors. To investigate the wider impact of indigenous resistance, however, we also calculate least cost paths from Spanish coastal landing points to inland colonial commodity frontiers—both with and without—indigenous resistance acting as an impediment to terrestrial movement and river access. We incorporate these results into our model and demonstrate that Indigenous sites of resistance not only protected the forest immediately around them, but spatially projected this protection throughout the forest, via the disruption of colonial route-ways.

These findings have both historical implications and further highlight the importance of contemporary Indigenous groups' role in protecting what remains of the Atlantic Forest today.

## 352. Chullpas in Series: A 3D-Based Morphometric and Spatial Workflow for Andean Funerary Architecture

*Cristian Gonzalez Rodriguez (University College London)*

*Marta Crespo Fernandez (Incipit-CSIC)*

Across the highlands of the Central Andes, above-ground funerary towers—locally known as chullpas—stand as enduring markers of ritual authority, lineage memory, and territorial presence. Despite their ubiquity and visibility across diverse ecological zones, their architectural diversity and spatial logic remain poorly systematised. While advances in digital recording technologies have produced high-resolution 3D models of these structures, the analytical reuse of such models for regional-scale comparison remains limited. This paper explores the methodological and interpretive potential of computational reuse of 3D data to analyse formal variation, volumetric design, and spatial arrangement within and across funerary landscapes in the Andes.

Based on a curated sample of 30 existing 3D reconstructions from the Andean Plateau, this research applies a pipeline of morphometric segmentation and geometric-vectorial analysis to investigate patterns in chullpa morphology and their spatial configuration. The sample includes chullpas that were originally recorded via structure-from-motion (SfM) drone photogrammetry and post-processed in Blender and CloudCompare, and which are now being reused as analytical objects. The selection spans different eco-political zones and sociocultural traditions, enabling a comparative approach to variation in funerary monumentality within the broader Andean sphere.

The methodology operates at two interrelated scales. First, individual chullpas are analysed through geometric segmentation and volumetric clustering, focusing on measurable variables such as base-to-height ratios, cavity-to-volume proportions, tapering profiles, and orientation of entrances. These descriptors allow us to test hypotheses regarding regional typologies, functional variation, and architectural standardisation. Second, the configurations of chullpa clusters are analysed through vector-based spatial analysis, assessing the relative alignment of structures, their angular deviation from cardinal axes, and the internal layout of clusters with respect to circulation, visibility, and access. This is complemented by basic spatial statistics and proximity measures to understand whether monument placement followed structured spatial logics or responded to local affordances and constraints. Preliminary results reveal three key patterns. First, certain regions exhibit greater formal homogeneity, with tightly standardised volumes and consistent orientation patterns, suggesting shared architectural templates and possibly more centralised planning principles. Second, other zones display significant variability within small clusters, pointing to diverse construction episodes, social heterogeneity, or looser regulatory frameworks. Third, in several cases, the spatial orientation of chullpas—especially entrance directionality—reveals alignments towards prominent landscape features, such as volcanoes or solar events, reinforcing previous findings about the cosmological structuring of funerary space. These findings invite reflection on how monument form and spatial logic co-articulated symbolic, social, and cosmological dimensions of Andean mortuary practice.

Rather than offering a complete typology or an exhaustive regional survey, this study presents a workflow prototype for low-cost, scalable, and reproducible comparative analysis using already available 3D data. Ultimately, this contribution positions computational morphometrics and spatial analysis not as replacements for contextual interpretation, but as tools to enhance it, opening new avenues for understanding how architecture encoded memory, hierarchy, and place in ancient Andean lifeworlds. By testing and proposing replicable methodologies for analysing chullpas "in series", this paper speaks to broader discussions about comparative monumentality, digital workflows, and computational rigor in the archaeology of the Americas.

### 356. Question-Driven Collaboration: Federated Virtual Survey with the Geospatial Platform for Andean History, Culture, and Archaeology (GeoPACHA)

*Nathaniel VanValkenburgh (Brown University)*

*Steven Wernke (Vanderbilt University)*

*James Zimmer-Dauphinee (Vanderbilt University)*

*Yuankai Huo (Vanderbilt University)*

*Junlin Guo (Vanderbilt University)*

*Matthew Ballance (Brown University)*

*Jacob Bongers (University of Sydney)*

*José Capriles Flores (Pennsylvania State University)*

*Cristian González Rodríguez (University College London)*

*Ericka Guerra Santander (Universidad Nacional San Agustín)*

*Frances Hayashida (University of New Mexico)*

*Manuel Mamani Calloapaza (Independent Scholar)*

*Giancarlo Marcone (Universidad de Ingeniería y Tecnología)*

*Raquel Mejía Aranguren (Independent Scholar)*

*Pablo Mendez-Quiroz Aranda (Universidad de Chile)*

*Gabriela Oré Menéndez (University of Nevada)*

*Jo Osborn (Texas A&M)*

*Alexis Reátegui Díaz (Independent Scholar)*

*Kevin Ricci Jara (Independent Scholar); Grecia Roque Ortega (Independent Scholar)*

*Jason Toohey (University of Wyoming)*

*Anthony Villar Quintana (Independent Scholar)*

This paper offers a critical reflection on the development and deployment of the Geospatial Platform for Andean Culture, History and Archaeology (GeoPACHA), a web platform for “virtual” archaeological survey of high resolution satellite imagery. In particular, we consider how the project’s ongoing, large-scale, collaborative work articulates with “on the ground” archaeology in distinct portions of the central Andean region. What questions is satellite survey well-suited to answering – and what forms of collaboration do online platforms afford? Are these approaches particularly (or even exclusively) well suited to regions with not only high levels of surface visibility but histories of political integration in antiquity, such as the central Andes? And how do we responsibly and ethically interface in this work with national heritage agencies, local communities and other stakeholders?

GeoPACHA began in 2018 with a specific set of research questions in mind – namely, how were the planned towns (reducciones) into which Indigenous people in the Andes were forcibly resettled in the late 16th century distributed within the viceroyalty of Peru? In turn, what might their topographic, environmental, and regional archaeological contexts reveal about both the processes of resettlement and their medium- and long-term consequences for Indigenous communities? To collect new data to address these questions, we built a web application to facilitate systematic visual survey of publicly available imagery. In the process, it became clear that it might be a useful tool for other researchers and questions.



Rather than following the lead of previous virtual archaeological surveys that had sought to identify all visible archaeological sites within a given territory, we decided to pursue a different path: a "federated" approach in which the platform would partner with existing teams of experts and students to help them address existing research questions that were well-paired to satellite survey. By doing so, we hoped to facilitate work that would draw off of—and contribute to—regional traditions of archaeology, complementing rather than seeking to replace programs of excavation, pedestrian survey, and materials analysis. We reached out to colleagues, obtained funding, and then brought together the leaders of eight different research teams to discuss project design. Together, we developed a common database structure, a set of survey standards, and a series of shared vocabularies for labeling archaeological loci. A key element of project design was to include two separate tiers of editorial review -- by "regional editors" and "general editors" in order to ensure that data were double-checked. Then, teams set to work collecting a broad range of data, including the distribution of defensive sites in the circum-Titicaca region, the organization of pastoral infrastructure along the Mercury Road between Huancavelica and Pisco, and the relationship between archaeological sites and lomas fog oases in the Peruvian central coastal region. Although we did not plan for the project to be adapted to the challenges of working in the Covid-19 pandemic, it proved itself well-suited to that task and the bulk of the first survey "season" (2020-22) was carried out during the height of that challenging period. A series of publications in 2023-24 (including a themed section of *Antiquity*) presented the results of this first stage of project work (Arkush et al. 2023; Marccone et al. 2023; Plekhov et al. 2021; Spence Morrow et al. 2021; Wernke et al. 2023; Whitlock, Van Valkenburgh, and Wernke 2023; Zimmer-Dauphinee and Wernke 2024).

In addition to collecting data for addressing specific archaeological research questions, the project's first stage also provided an opportunity to gain critical insights into the methodology of virtual survey more generally. One challenge that teams faced during survey was maintaining focus and consistency, particularly in areas with relatively low densities of archaeological features.

Comparing human-generated GeoPACHA data with data generated via a Convolutional Neural Network trained for identifying archaeological structures in the same imagery, Zimmer-Dauphinee et al (2023) found both approaches complementary. While archaeologists proved better at recognizing a broader range of features than the CNN, they missed many identifications due to fatigue.

Based on these experiences, we developed a series of best practices and also began a new stage of research focused on the development of AI models to assist a new series of teams in pursuing their research questions. These efforts have focused on the development of DeepAndes, a vision foundation model for identifying a wide range of archaeological features in satellite imagery through a variety of downstream tasks, including image retrieval, object detection and (Guo et al. 2025). Through these means, GeoPACHA is mapping features across a much broader, more continuous area, in turn enabling the resulting datasets to be better paired with environmental data generated from satellite imagery. In the process, the project has shifted again: we are generating more data than the current teams will be able to fully review and edit, and which extend beyond the valleys and smaller regions in which we have conducted fieldwork. As a result, GeoPACHA eventually needs to shift to become a platform with a broader community of users. How should we do so in a way that—more than simply avoiding placing heritage at further risk—empowers stakeholders by providing improved tools for heritage management?

### 377. Tracing empires: settlement dynamics in the Yauhtepec valley (Mexico) between 1500 BC and 1520 AD

*Giacomo Bilotti (Aarhus University)*

*Natália Fedorová (Aarhus University)*

*Iza Romanowska (Aarhus University)*

*Michael Smith (Arizona State University)*

The Yauhtepec Valley is located in the central part of the state of Morelos in Central Mexico. A full coverage systematic survey was carried out in the 1990s over 150 km<sup>2</sup> which encompassed all the alluvial and foothill areas of the valley (Smith et al. 2021). A total of 415 sites were identified dating from the Early Formative to the Colonial period (1500 BC – 1520 AD). The sites include all sorts of inhabited settlement, from small hamlets/farmsteads to large cities up to 130 ha. While preliminary analyses have been conducted, the application of current analytical methods allows new insights on settlement organisation, demographic trends and persistence during important historical moments in the region, including the appearance of large monumental centres during the Middle Formative, the scale of the influence of the Teotihuacan Empire in the region during the Classic period (200 - 600 AD) and the Aztec expansion during the Middle and Late Postclassic periods (1150 - 1520 AD).

In this paper, we aim to identify the fingerprints of imperial control in the Yauhtepec valley, and in particular the differences in settlement organisation as opposed to phases without large macroregional institutions. In particular, we will focus on settlement continuity, size and persistence over time. The results can be used to test two hypotheses: (1) Teotihuacan conquered the Yauhtepec Valley and brought about changes in settlement and (2) the “Post-classic world system” (Smith & Berdan 2003) generated greater settlement continuity and persistence. Other patterns that we wish to explore include

the impact of larger sites (e.g., Yauhtepec) on the rest of the valley and the nature of the urban systems during different phases.

The archaeological data's inherent temporal uncertainty poses challenges when addressing fine-grained questions about settlement chronology and persistence. In order to overcome them we recur to a formal simulation based model that can produce robust inferences while accounting for uncertainty.

#### Methods

Based on the current state of the art in addressing temporal uncertainty in typo-chronologically dated sites (Crema, 2024), one might turn to aoristic analysis to address these issues. Developed initially in crime science and adopted in archaeology 20 years ago, the technique had a discrete success in generating time-frequencies of typo-chronological data whilst accounting for chronological uncertainty. Aoristic analysis has, however, some major limitations as it is prone to biases derived by how archaeological periodisations are constructed, and as a descriptive statistic, it does not account for issues such as sampling error. Building on recent advances in aoristic analysis (the “Bayesian alternative” suggested by Crema, 2024), we consider the following sources of uncertainty and biases that affect typo-chronologically dated sites:

1. Phase boundary uncertainty. Typo-chronological phases are fuzzy and should not be treated as discrete blocks.
2. A site may have been occupied during only part of a phase or abandoned before the end of a phase. Phase boundaries cannot be safely used as direct evidence for the starting and ending date of a site.

Given the strict survey methodology and the previous work on building a strong typo-chronological framework based on local pottery, we can safely assume that the dataset we are using do not suffer from “phase assignment uncertainty”, the last type of uncertainty described by Crema (2024).

Failing to account for this may produce spurious results that would affect our interpretation. Consider the following example: The Middle Formative period (1100-500 BC) lasted for 600 years, the Late Classic for 150 (450-600 AD). A hamlet in the earlier period is unlikely to have lasted for six centuries. It is even more unlikely that all hamlets dating to either period started at the same time (1100 BC or 450 AD) or were contemporaneously occupied.

To address these issues, we employ a Monte-Carlo simulation approach as follows:

1. Phase definition. Phase boundaries are resampled assuming that their uncertainty is tied to the overall length of the typo-chronological phase, with short and well-dated periods being assigned a smaller deviation from the year estimate than longer ones. In the Yautepec survey, longer phases result from lower chronological resolution in pottery types, hence their greater temporal uncertainty compared to short, well-defined phases.
2. Site-level sampling. For each iteration, site start and end dates are sampled from a uniform distribution bounded by the resampled phase limits, with the constraint that duration must be positive.
3. The simulation is iterated and the results aggregated.

Most sites in our datasets are multi-phase (349 vs 178 single phased sites) and phase length varies from 80 to 600 years. This and the amount of cultural variation observed in the long time considered prevents us from constraining site length a priori (e.g., sampling from a defined distribution around a mean value).

The results and their underlying uncertainty are then used to answer the specific research questions about the settlement patterns and organisation of the Yautepec valley. Notably, we analyse changes over time in site hierarchy (rank–size distributions), inter-settlement distance patterns, settlement

persistence, demographic and urbanisation trends (using site area as a population proxy) and agricultural potential within site catchments.

This will allow us to test whether the presence of a large macroregional institution (the Aztecs) affected the persistence, structure and spatial organisation of sites, and whether it is possible to identify Teotihuacan's footprint in the valley.

Preliminary results suggest that there was a settlement reorganisation during both imperial periods, with the establishment of new capitals or with the expansion of settlements that reached their maximum size (apogee) during these phases.

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## 408. Memory and Control: Digital mortuary landscapes from Wari to Colonial Peru in the Huarmey & Culebras valleys

*Miłosz Giersz (University of Warsaw)*

*Patrycja Prządka-Giersz (University of Warsaw)*

*Wiesław Więckowski (University of Warsaw)*

*Roberto Pimentel Nita (University of Warsaw)*

*Maciej Kałaska (University of Warsaw)*

*Jakub Stępnik (University of Warsaw)*

*Jędrzej Szymanek (University of Warsaw)*

*Izabela Kurjan (University of Warsaw)*

*Julia Chyla (University of Warsaw)*

We present a joint view from two ongoing projects in north-central coastal Peru that bracket a long temporal arc: from Middle Horizon (Wari, AD 650–1050) mortuary landscapes around Castillo de Huarmey to early-colonial transformations at Chacuas Jirca (upper Culebras). Our shared question is how computational prospection and documentation can illuminate the politics of memory and control across periods while remaining feasible in contexts with uneven infrastructure, multilingual audiences, and sensitive funerary data. We argue that light-weight, field-calibrated digital workflows (mobile GIS, UAV RGB/multispectral, DEM/DSM, 3D scanning) can scale across environments and project teams, and that their community and training components are as critical as their analytics for the Americas.

Methods and materials

CHULLPA (Huarmey & Culebras valleys; Middle Horizon & Late Intermediate Period mortuary sites).

Seventeen funerary locales were selected across coastal plain, mid-valley crossroads, and upper-valley settings. We used: (1) mobile GIS with a customised Survey123 schema for rapid, structured surface observations; (2) UAV mapping to produce site-scale orthophotos, DSM/DEMs (3) 3D scanning for creation of digital twins of funerary architecture; and (4) environmental zonation to compare condition, disturbance, and assemblage signals. The pipeline was designed for disturbed contexts, emphasising speed, repeatability, and minimal on-site compute.

Chacuas Jirca (Colonial-period node with pre-Hispanic origins).

In the upper Culebras, we combined (1) UAV multispectral imaging (index composites for adobe/stone contrasts and vegetation proxies), (2) mobile-GIS survey (3) reconnaissance, (4) terrestrial 3D scanning for architectural elements, (5) geological sampling to characterise local building stone and mortars, and (6) test excavation within funerary architecture to ground-truth remote signals. Across both projects we use consistent coordinate control, per-feature provenance, and bilingual field forms to align outputs for reuse by local partners.

### Results

Huarmey–Culebras (CHULLPA).

The combined mobile-GIS and UAV datasets improved the condition map and internal structure of highly disturbed cemeteries. Material signatures vary by environment: coastal sites yielded abundant textile remains, mid-valley loci concentrated organics, and upper-valley contexts produced highland-style ceramic traits, consistent with coastal–sierra linkages during the Middle Horizon. Orthophotos and DSMs refined feature boundaries and micro-topography, enabling prioritised sampling and a candidate set of excavation blocks.

Chacuas Jirca (Colonial transition).

Multispectral UAV composites and 3D scans delineated architectural sectors and circulation routes not visible in RGB alone, highlighting re-use and

modification of earlier mortuary spaces during the early-colonial period. Geological sampling constrained source areas for construction materials, and the first test excavation within funerary architecture confirmed the interpretability of spectral contrasts in buried wall segments.

Cross-project synergies.

Using compatible schemas and simple QA checks allowed us to compare valley-to-valley patterns and to move personnel and students between teams with minimal retraining. The workflow proved robust to patchy connectivity, mixed-experience crews, and the need for multilingual (ES/EN) documentation and outreach.

Discussion

Bilingual, FAIR-leaning documentation. Bilingual forms and per-feature provenance ease handover to regional archives and authorities; where full FAIR deposition isn't yet possible (permits, sensitivities), we still publish method templates and synthetic examples.

Workflow choices (training students, bilingual outputs, co-authorship with local researchers, and sensitivity filters for funerary coordinates) and local outreach embody the ethical commitments, beyond slogans to concrete measures.

What we learn about memory and control.

Across periods, mortuary landscapes act as infrastructure for power: in the Wari sphere, funerary nodes articulate coastal–highland ties; in early-colonial Culebras, repurposed funerary spaces and route reorganisation speak to imposed identities and new administrative geographies. Computational mapping lets us see these as continuities and breaks in a single corridor system, not isolated episodes.

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## 450. Modeling hunter-gatherer-fisher communities in the South Pacific: A high-resolution spatial approach to studying coastal settlements in the Atacama Desert

*Pablo Mendez-Quiros (Universidad de Chile)*

*Cristian González (University College of London)*

*Estefanía Vidal (Universidades Alberto Hurtado)*

*Mauricio Uribe (Universidad de Chile)*

*Francisca Santana (Pontificia Universidad Católica de Chile)*

*Vesna Obilinovic (Universidad Arturo Prat)*

*Claudio Wande (Universidad de Chile)*

*Diego Mayorga (Pontificia Universidad Católica de Chile)*

*Montserrat Javalquinto (Universidad de Chile)*

*Camila Ramírez (Universidad de Chile)*

The South American Pacific coast has been a key area for the archaeological analysis of the Andean region. From Ecuador to Chile, along thousands of kilometers of coastline, diverse human groups settled from the late

Pleistocene onward, sharing a close relationship with the sea and its resources for thousands of years.

We present the first results of the Tarapacá Coastal Archaeology project, which aims to intensively study the human settlements along the coast of the Atacama Desert, covering 250 km of coastline (19.3°–21.4°S). The extremely arid environmental conditions and the current low population density are key factors in the extraordinary preservation of archaeological remains, providing excellent clarity regarding past human activities.

Through the study of archaeological settlements from a long-term perspective, we seek to understand the socio-spatial dynamics of coastal communities in the Atacama Desert and, based on high-resolution archaeological information, contribute to the ecological management of the coastal desert territory, both past and present. Indeed, we understand that past territorial occupation dynamics can provide insights for managing present occupation dynamics.

By conducting a high-resolution archaeological survey of the Tarapacá Region coastline, we aim to understand the processes of territorial/maritime occupation through spatial analyses that allow us to document and model human settlements in spatial and chronological terms, deepening our understanding of coastal societies and the changes in coastal occupation strategies. From a regional scale of analysis, we seek to understand the heterogeneity of the coastal archaeological record, which is generally described as stable and conservative, thus obscuring a diversity of histories in territories with different spatial configurations and territorial connections.

By using high-level equipment such as RPAS and LiDAR sensors, we propose a qualitative leap in the coverage and digitization of archaeological heritage, generating spatial models for the detailed study of social dynamics, from the earliest pre-Hispanic settlements to recent historical times.

We present the initial results of our fieldwork focused on the study of settlements through surface recording, photogrammetry, and LiDAR surveying, combined with stratigraphic, material, functional, and chronological characterization through archaeological excavations.

This information will be structured and presented in an open-access archaeological inventory, accompanied by thematic maps and digital (3D) models of coastal human occupation over time. These models are the starting point for the development of current and future analytical tools that will allow us to answer questions about the distribution and spatial organization of archaeological information and its relationship with multiple layers of information.

In this way, we seek to decisively influence the territorial planning of the coastal zone, which faces significant challenges stemming from the imminent expansion of urban and industrial infrastructure. We aim to do this by raising awareness about the importance of guiding the growth of public spaces, cities, coves, and beaches toward ecological, harmonious, and sustainable development. For this reason, we propose lines of work that involve territorial organizations, public services, and specific authorities (municipal and regional, among others) to advance toward the integrated heritage protection of the coastline within the framework of future urbanization projects.

## 454. Applying Gaussian Splatting at a Coastal Maya Site El Meco

*Ashuni Emmanuel Romero Butróni (Centro INAH Quintana Roo)*

*Nelda Issa Marengo Camach (University of New Mexico)*

During the Research and Conservation Project El Meco (PICME) conducted in 2023 and 2024, we digitally documented maintenance activities on buildings and numerous systematic excavations at the El Meco archaeological site in



Quintana Roo, Mexico. Our main goal was to generate three-dimensional digital models to facilitate subsequent analyses. Additionally, we aimed for these models to serve as effective tools for the digital dissemination and communication of our work and findings. By applying the volumetric rendering technique known as Gaussian Splatting, we have successfully engaged both specialized and general audiences with the cultural heritage of the ancient settlement of El Mecó in an accessible, visually compelling manner.

The development of direct rendering techniques, such as Lee Alan Westover's pioneering work in 1991, laid the foundation for subsequent studies (Botsch et al., 2005). More recently, the work of Kerbl and colleagues (2023) marked a turning point for this technique, significantly influencing the 3D modeling industry and applications within three-dimensional environments, including augmented reality (AR) and virtual reality (VR). This direct rendering technique is characterized by the treatment of splats generated from original two-dimensional images; each splat acquires spatial coordinates (X, Y, Z), opacity, color, shape, and orientation. These distinctive features allow the resulting models to exhibit dynamic luminance variations with changes in viewing angle, generating visual representations of notably photorealistic quality. This technique facilitates rapid processing of large volumes of information, resulting in lightweight models compatible with various programs and platforms, while maintaining realistic real-time rendering capabilities.

Using this technique, we have processed several image sets from diverse contexts, employing specialized software such as Luma Lab, Polycam, Scaniverse, NerfStudio, and Postshot, achieving comparable results in terms of quality and file size. However, more pronounced differences emerge regarding the devices used for image capture and the scale of the areas being documented.

Various platforms have been developed to facilitate the visualization and sharing of products generated by this technique more straightforwardly and realistically, such as Gracia or Arrival Space. These tools have enabled us to showcase El Mecó's cultural heritage to colleagues and the general public through virtual reality lenses or online access.

Currently, this technique has been systematically applied to the documentation and visualization of cultural heritage in only a few instances (Jamil and Brennan, 2025). Therefore, implementing this technology in our project represents both a challenge and an opportunity to digitally preserve a portion of the cultural heritage of the El Mecó archaeological site.

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## S22: Ethics in Digital and Computational Archaeology

*Eduardo Herrera-Malatesta, University of Bonn*

*Aleks Michalewicz, The University of Melbourne*

*Alicia Walsh, Leiden University*

*Madisen Hvidberg, University of Calgary*

**Location:** Hörsaal BIG

**Session Format:** Standard

The rapid development of technology in archaeology has introduced both new opportunities and new ethical challenges. The accessibility of advanced tools, from large-scale digitisation and remote sensing to artificial intelligence, has shifted the central question from “Can I?” to “Should I?” While frameworks such as the London Charter, the FAIR and CARE principles, and the CAA Ethics Policy offer valuable guidance, they often remain broad in scope. Their flexibility allows application across diverse scenarios, but it can also make translating them into everyday practice difficult. Ethical review processes frequently prioritise legal compliance, such as GDPR and privacy, reducing ethics to a procedural box-ticking exercise rather than a starting point for deeper reflection. This session reframes ethics as an ongoing, integral aspect of research design and practice, not an afterthought. We invite presenters to share first-hand accounts of ethical dilemmas encountered in digital and computational archaeology: what worked, what did not, and how solutions were reached. By openly discussing challenges and even “failings,” we can collectively identify pathways toward more equitable, sustainable, and context-aware practice.

Topics include (but are not limited to):

- Implementing FAIR and CARE principles in practice,
- Environmental sustainability in digital projects,

- Codes of conduct for field, lab, and online work,
- Navigating ethical research in geopolitical conflict zones,
- Community engagement, co-creation, and restitution,
- Digitisation of human remains and culturally sensitive materials,
- Decolonial approaches to digital heritage,
- Lessons from other disciplines.

While we are interested in grounded, practice-based perspectives, we welcome theoretical discussions on any related topic or questions. For example, how do archaeologists adapt ethical guidelines to fit specific social, political, and environmental contexts? How can grassroots activism, public engagement, and institutional change work in tandem to shape ethical practice? What creative strategies emerge when principles meet the realities of funding bodies, governmental institutions, or community expectations? We also encourage reflections on the intersections between digital and broader archaeological ethics. Restitution, equitable access, intellectual property, accessibility for people with disabilities, and the stewardship of conflicted heritage all gain new dimensions when digital technologies are introduced. By examining these intersections, we can better anticipate the ethical implications of emerging tools such as 3D documentation, virtual and augmented reality, AI-driven analysis, and open data platforms.

With this session, we aim to foster a collaborative space for sharing experiences, learning from one another, and building adaptable roadmaps for the ethical use of digital technologies in archaeology. Through open dialogue, critical reflection, and cross-disciplinary exchange, we hope to strengthen ethics as a living practice, one that guides our decisions, shapes our relationships with communities, and ensures the responsible stewardship of archaeological heritage in a rapidly changing digital world.

1. Common Ground: Examining ethics in digital Dutch archaeology  
Alicia Walsh

2. Between Democratization and Scientific Integrity: A Critical Re-evaluation of the London Charter in the Age of AI and Resource Scarcity  
Arman Džaferagić

3. When the living are used to restore the dead of the past: a methodological approach to the use of post-mortem CT scans. Ethical issues surrounding the creation of a library of scientific 3D models of immature subjects, from skeletons to bodies.  
Geraldine Sachau-Carcel

4. Preserving the Void: Ethics and Temporality of Digitally Reconstructing Post-Conflict Cultural Heritage  
Paraskevi Gavra

5. Caribbean Digital Archaeology: Ethical challenges and best practices  
Eduardo Herrera Malatesta

6. Data Feminism Frameworks, Indigenous Data Sovereignty, and Data Ethics in Digital Archaeology  
Aleks Michalewicz

**08:30 – 08:50** 52. Caribbean Digital Archaeology: Ethical challenges and best practices  
*Eduardo Herrera Malatesta (Leiden University)*

**08:50 – 09:10** 145. Between Democratization and Scientific Integrity: A Critical Re-evaluation of the London Charter in the Age of AI and Resource Scarcity  
*Arman Džaferagić (Deutsche Schiffahrtsmuseum (DSM) / Leibniz-Institut für Maritime Geschichte)*

**09:10 – 09:30** 173. Common Ground: Examining ethics in digital Dutch archaeology  
*Alicia Walsh (Leiden University)*

**09:30 – 09:50** 388. Preserving the Void: Ethics and Temporality of Digitally Reconstructing Post-Conflict Cultural Heritage  
*Paraskevi Gavra (University of Cologne)*

**09:50 – 10:10** 451. Data Feminism Frameworks, Indigenous Data Sovereignty and Data Ethics in Digital Archaeology  
*Aleks Michalewicz (University of Melbourne)*

**10:10 – 10:30** Discussion

## 52. Caribbean Digital Archaeology: Ethical challenges and best practices

*Eduardo Herrera Malatesta (Leiden University)*

The expansion of digital and computational methods has transformed archaeological practice worldwide, but it has also introduced new ethical challenges concerning data sovereignty, representation, and power asymmetries. This paper explores these issues through the lens of Caribbean digital archaeology, a region historically shaped by colonisation, extraction, and epistemic dependency. Drawing on recent debates in digital ethics (e.g., Dennis, 2020) and decolonial critiques of archaeological practice (e.g., Gnecco, 2015), it examines how digital technologies risk reproducing historical inequities under the guise of innovation and openness. The first part of the paper outlines two interrelated dimensions of ethical concern in digital archaeology: scientific and political. The scientific dimension involves questions of

data management, transparency, and methodological accountability, particularly the use of “black box” algorithms, artificial intelligence, and machine learning in archaeological interpretation. These technologies can obscure decision-making processes and inadvertently reinforce biased narratives when datasets are incomplete or uncritically applied. The political dimension addresses the broader implications of who defines ethical standards, whose data are shared, and who benefits from open-access mandates. As argued by Hamilakis (2007) and (González-Ruibal, 2018), ethical codes often universalise Western moral frameworks, marginalising alternative epistemologies and perpetuating asymmetrical relations between academic centres and local communities. The second part situates these debates within the Caribbean, where digital representations intersect with a long colonial history of classification, extraction, and silencing. The digital reconstruction of Indigenous pasts, through 3D modelling, GIS mapping, or online databases, can both challenge and replicate colonial narratives. Practices such as mandatory open-access data policies, often dictated by Global North funding agencies, risk undermining national sovereignty and exposing sensitive cultural information. This dynamic exemplifies what has been called digital neocolonialism (Adam, 2019), encompassing both the appropriation of data (“data colonialism”) and the reproduction of Western epistemic frameworks through algorithmic systems (“algorithmic coloniality”).

The paper then presents a framework of best practices for ethically grounded digital archaeology in the Caribbean. These include: (1) transparent and context-sensitive data management strategies that respect local laws and community consent; (2) tiered access systems in digital repositories to protect vulnerable information; (3) participatory approaches that involve Indigenous and local stakeholders from project inception to data dissemination; and (4) the inclusion of digital ethics training within both archaeological and community education programs. Crucially, consultation must move beyond mere information-sharing toward active decision-making, ensuring that digital heritage initiatives contribute to social justice and local empowerment rather than reinforcing dependency. Ultimately, this paper argues that ethical digital archaeology must be relational, reflexive, and political.

The Caribbean offers a compelling case study for rethinking global digital ethics from the perspective of regions historically positioned at the margins of knowledge production. By confronting issues of representation, data sovereignty, and algorithmic bias, digital archaeology can move beyond universalist ethics toward more plural, situated, and equitable forms of knowledge-making, where technology serves as a bridge rather than a boundary between communities, pasts, and futures.

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## 145. Between Democratization and Scientific Integrity: A Critical Re-evaluation of the London Charter in the Age of AI and Resource Scarcity

Arman Džaferagić (*Deutsche Schiffahrtsmuseum (DSM) / Leibniz-Institut für Maritime Geschichte*)

### Context:

The London Charter for the Computer Based Visualization of Cultural Heritage was established in 2009 (Version 2.1) as a foundational ethical and methodological response to a growing crisis in digital heritage: the risk of intellectual opacity posed by the proliferation of photorealistic 3D visualizations. Its core mandate was to ensure that computer-based visualization would be and would be seen to be, as scientifically rigorous and robust as any other established research discipline (Denard 2012). The subsequent 15 years have been defined by a profound technological democratization. The advent of low cost photogrammetry, free and open source software, and the integration of LiDAR sensors into consumer mobile devices has dramatically lowered the technical and financial barriers to 3D capture. This has successfully fulfilled the Charter's Principle 6 (Access), empowering a wide range of institutions, especially smaller museums with limited resources, to engage in 3D digitization projects.

However, the field now confronts a new technological disruption: the rise of generative Artificial Intelligence (AI). This marks a fundamental paradigm shift from representative visualization, capturing what exists, to generative visualization, which algorithmically creates, completes, or infers what is missing. This new paradigm presents an unprecedented challenge to the Charter's core tenets of transparency and evidence based representation. The very success of the democratization era has created a new vulnerability. The vast, but often poorly documented, corpus of digital heritage created over the last decade now serves as training data for these opaque new AI systems.

This threatens to amplify the methodological weaknesses of the past at an industrial scale, making a critical re evaluation of the Charter's implementation both timely and urgent.

### Main Argument:

This paper's central argument is framed as a critical paradox: the singular success in democratizing access to 3D capture (Principle 6: Access) has directly exacerbated a systemic and widespread failure to adhere to the Charter's core principles of research sources (Principle 3: Research Sources), scientific documentation and intellectual transparency (Principle 4: Documentation), and long term sustainability (Principle 5: Sustainability).

The ease with which visually appealing models can now be created has fostered a false sense of compliance, masking deep methodological deficits. This paradox has manifested as a pervasive "Paradata Crisis". Paradata, defined as "data about the process" of creation, is essential for scientific verification (Huvila 2025).

The systemic failure to capture, structure and link this procedural information to digital assets has rendered a majority of the digital heritage created in the last 15 years scientifically unverifiable, reducing them from reliable research sources to mere aesthetic objects.

This non compliance is not the result of individual failings but of deep seated structural barriers, primarily chronic resource scarcity and a profound "competence gap" within small and medium sized cultural institutions. This dynamic is worsened by an "inversion of competence requirements": contrary to popular belief, low cost tools require more, not less specialized human expertise. Lacking the automated calibration and metadata capture of high end systems, they place a greater methodological burden on the user to perform and meticulously document manual steps to produce scientifically valid results. The institutions most in need of these tools are precisely those least equipped to meet these elevated demands. AI now enters this landscape not as a new problem, but as a radical accelerant of the existing crisis. The "black

box" nature of many generative models makes documenting algorithmic provenance exceptionally difficult, while their function systematically blurs the line between evidence ("Reality Capture") and algorithmically inferred hypothesis ("Recreation of the Past"), representing a fundamental assault on the Charter's principles.

#### Applications or Implications:

The primary implication of this analysis is that the vast digital output of the past 15 years is at severe risk of entering a "digital dark age". It faces a dual threat: becoming scientifically devalued due to the paradata crisis and becoming physically inaccessible due to technological obsolescence, a direct consequence of the systemic failure to implement Principle 5. This situation demands a fundamental strategic reorientation for the field. The focus of funding, policy and institutional strategy must shift from the novelty of digital creation to the systemic, long term challenges of digital stewardship.

The problem is no longer primarily technical but has become organizational, financial and political. In response, this paper proposes a three pronged strategic roadmap for achieving compliance and future proofing the discipline. First, to operationalize transparency, the field must adopt standardized semantic frameworks like the Heritage Digital Twin (HDT) and the CIDOC Conceptual Reference Model (CRM). These provide a robust, machine readable structure for documenting provenance, making the Charter's principles technically achievable and directly countering the opacity of AI (Niccolucci et al. 2023). Second, to ensure sustainability, the burden of long term preservation must be shifted from individual institutions to centralized, certified digital repositories operating on established standards such as OAIS (ISO 14721), PREMIS and the FAIR Principles (Findable, Accessible, Interoperable, Reusable). Third, and most critically, the systemic competence gap must be closed through sustained investment in centralized training initiatives and by integrating these essential digital and methodological competencies directly into the academic and vocational curricula for the next generation of heritage professionals.

Ultimately, the London Charter, far from being obsolete, has become more critical than ever. Conceived to govern human led interpretation, its core focus on process over product provides the most robust ethical framework for navigating the challenges of automated, algorithmic interpretation. It equips the heritage sector with the intellectual tools to demand accountability from the "black box", shifting the critical question from "What does it look like?" back to the scientific imperative of "On what evidence, and by what process, was it made?".

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## 173. Common Ground: Examining ethics in digital Dutch archaeology

*Alicia Walsh (Leiden University)*

The ethics of archaeology are, as Richardson (2018) pointed out, always dependent on context and historical and social background of the site, work,



authors and project participants. While ethical considerations themselves are contextual, so too is the amount of attention that (digital) archaeological ethics receives as a topic of research. In settler and post-colonial societies around the world, many archaeologists are already becoming more reflective about their ethical technology use (Csoba DeHass et al. 2025), partly thanks to the CARE principles as a guiding practice. Likewise, museums are also grappling with ethical considerations when combining digital methods with their roles as stewards of collections with colonial and contested histories. However, there is a limited amount of research into the social impact of both digital methods and digital ethical frameworks in European archaeology, and as Dennis (2020) notes, determining what constitutes ethical consensus on work with digital tools is the responsibility of all those working with them. While reaching an ethical consensus may not be attainable or even appropriate in societies with numerous cultures and values, there does need to be greater responsibility when working with these tools, as well as clarity over what falls under digital ethics and why these topics are important to consider. In the Netherlands, many archaeologists claim that digital ethics is not as relevant because we do not work in contexts such as those mentioned above, apart from research including human remains. The most attention it receives is as a procedural task in institutions, which prioritizes legal issues relating to personal data. More philosophical, hard-to-answer topics are often met with discomfort or indifference. However, when diving deeper into discussions on this, it becomes apparent that there are other ethics that are visible in Dutch archaeology and that many archaeologists do consider this to be a topic worthy of attention.

The aim of the research highlighted in this paper is to identify what the ethical issues are related to the digital recording techniques of 3D and remote sensing within a Dutch archaeological context. It will discuss how potential issues are viewed amongst professionals in the Netherlands, including the Dutch Caribbean, and possible best practices when it comes to handling these ethical concerns. To do so, a mixed method approach was used including an online survey and in-person qualitative interviewing with

archaeological and heritage professionals in the commercial, academic and museum sectors. Participants were asked questions to establish the current state of digital archaeological recording in the Netherlands, such as who is using 3D and remote sensing, for what purposes, and what challenges and ethical considerations are visible across companies and sectors. The ethics that have been identified so far include environmental sustainability, data access and archiving, religion and the treatment of human remains, and privacy. As this research is ongoing, planned future steps for determining ethics will also be discussed such as the need for cross-cultural analyses into the ethics of 3D and remote sensing to determine how geographic, cultural and historical influences may shape our perceptions and best practices. These topics can then be investigated further and categorized into an approachable way so that researchers can view them not as uncomfortable subjects to avoid or mere boxes to check in order to secure funding. However, the aim of this research is not to generalize perceptions or determine what is right and wrong, since there is no single cultural experience or value amongst archaeologists or the public. On the contrary, there are many perceptions and values amongst archaeologists in the Netherlands, indicating that ethics is as relevant in this context as in other areas. It instead argues that the increase in using digital tools has increased our need to think critically about them, and that more attention needs to be paid to digital archaeological ethics, especially in areas wherein it has so far been limited.

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### 388. Preserving the Void: Ethics and Temporality of Digitally Reconstructing Post-Conflict Cultural Heritage

*Paraskevi Gavra (University of Cologne)*

In the last decades, numerous archaeological sites have been demolished in geopolitical war zones, driven by political and religious motives. The destruction of cultural heritage is a common practice in such contexts, serving as a direct attack on the identity and the collective memory of a state. In response, there is a steep increase in the use of digital tools for safeguarding cultural heritage for future generations. Digitizing archaeological sites that are inaccessible due to war may be considered a beneficial practice since it allows data to be shared globally, democratizing access to heritage. While the benefits of digital documentation are known, the ethical impact of digitally reconstructing post-conflict sites remains an issue insufficiently examined.

The Arch of Palmyra was demolished by the Islamic State (ISIS) in September 2015. Following its destruction, the Institute of Digital Archaeology recreated the monument using 3D printing technology. The replica was displayed in Trafalgar Square and other locations, sparking debate about the ethical framework surrounding the digital and physical reconstruction of destroyed heritage sites. It has been argued that the reconstruction failed to do justice to the original site or to the affected community (Khunti, 2018).

The present study, which was first conducted as a project for my Master, aims to open a discussion on the ethical implications concerning digital reconstructions of conflict-affected cultural sites. Should all cultural heritage material be digitally reconstructed and most importantly by whom (Isakhan, 2022)? The digital element shifts the attention from the community's

commemoration and mourning needs to third-party institutions' interventions for heritage preservation and representation which are often driven by political or soft power agendas reinforcing forms of digital colonialism. Such practices raise the question of how can the affected communities participate in the reconstruction process or retain control over the digital heritage while still benefit from global dissemination?

Prompted by the event of the 3D printing of the Arch of Palmyra, this theoretical discussion attempts to address the concept of ethical temporality as well. The replica was created and displayed in London only a month after the retaking of Palmyra by Assad's forces- while the region was still in conflict. Time itself transforms into a methodological and even an ethical medium in the digital age. It is up to discussion to evaluate the role of timing concerning the creation of a digital product and whether it extends or suppresses the community's identity (re-)formation and grief. Furthermore, a digital reconstruction may be rendered as a temporal intervention in the historic stratification of a society. The technical-visual element tends to freeze the time within a post-conflict frame of the site, risking cultural appropriation and re-writing narratives that marginalize the cultural background of the pre-destruction archaeological site.

All of the above leads to the question of whether all destroyed cultural heritage monuments should be digitally reconstructed after all. The decision to reconstruct holds a specific significance as both an ethical and temporal matter. A deliberate non-reconstruction may preserve the historical rupture that symbolizes loss and grief. The study is an effort to answer or extend the aforementioned questions. Ultimately, this contribution in the CAA2026 engages with ethical temporality and endeavors to foster a dialogue of whether the absence of digital reconstruction may be more culturally responsible for the affected community than the production of a digital replica.

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## 451. Data Feminism Frameworks, Indigenous Data Sovereignty and Data Ethics in Digital Archaeology

*Aleks Michalewicz (University of Melbourne)*

Existing frameworks such as CARE and FAIR offer guidance for data engagement, but tensions between them remain. The FAIR principles (Findable, Accessible, Interoperable, and Reusable) prioritise machine-actionability, while the CARE principles (Collective Benefit, Authority to Control, Responsibility, Ethics) centre Indigenous knowledge systems and community authority in just, ethical, and relational data governance. Implementing these principles in archaeology poses challenges, and available and emerging technologies can easily exacerbate extractive data practices and problematic modes of data handling, processing, analysis, storage and return. Moreover, meaningful integration of CARE and FAIR requires navigating tensions between institutional systems, community decision-making processes, funder timelines, diverse cultural protocols and governmental requirements.

This paper draws on D'Ignazio and Klein's Data Feminism principles (2020) as complementary analytical tools to examine digital ethics in archaeology, specifically with respect to the relational components of our work. The feminist principles operate alongside Indigenous frameworks; they do not replace them. The aim here is to explore how explicitly incorporating data feminism

principles can help us to better understand not just our data, but our research practices. The seven data feminism principles function as provocations:

1. Examine power
2. Challenge power
3. Elevate emotion and embodiment
4. Rethink binaries and hierarchies
5. Embrace pluralism
6. Consider context
7. Make labour visible

These principles demand that we identify and contest power (principles 1 and 2), and question categories and hierarchical structures that shape archaeological practice (principle 4). These speak to cultural heritage work being affective, with participatory co-design centring embodied knowledge and lived experience (principle 3). They require co-creation to allow for multiple epistemologies and challenging dominant narratives (principle 5). They situate archaeological datasets within specific cultural, political, and environmental circumstances (principle 6). And, they demand recognition of all intellectual and physical labour (principle 7).

The Data Feminism framework can help integrate CARE and FAIR in revealing how FAIR's technical specifications must be approached through attention to the relationships through which data are created and shared, over the entire research lifecycle. The seven data feminism principles reflect the multivocality of data and draw our attention to the relationships embedded within and around data practices. They echo the CARE principles and Indigenous data sovereignty frameworks in emphasising that information, data, and knowledge are not neutral assets but situated within specific power relations where control and interpretive authority become key ethical concerns. Following Indigenous-led frameworks, data feminism principles can contribute to archaeological digital and data ethics becoming a more relational practice.

Archaeology, and digital archaeology, have much to offer in terms of working with sensitive data, but we can also look to other areas, such as health, education and arts research, which navigate similar challenges in balancing protocols with community-driven approaches (e.g., Homan 2022). Such fields offer valuable models for digital archaeology and a case study from Kiribati demonstrates how feminist data principles can inform ethical research that centres community authority, data care and data return.

As AI and other technologies increasingly blur the lines between small data and big data, meaningful collaboration is required to address impacts based on intersecting identities (Drage and McInerney 2023). Cross-disciplinary lessons can inform practical pathways for building ethical, people-centred approaches in digital archaeology where feminist data frameworks can help ensure that technologies serve, rather than extract from, communities.

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## RT24: Real-World Perspectives on Building Research Data Infrastructures: Community Practices, Legal Contexts, and Implementation

*Fabian Fricke, German Archaeological Institute*

*Agnes Schneider, Leiden University*

**Location:** Hörsaal 02

**Session Format:** Round table

### Background and Motivation

Archaeology, like all sciences, is entering an era where the volume, complexity, and interconnectivity of data are central to research progress. From excavation records and 3D models to GIS layers and analytical datasets, archaeological research increasingly depends on the ability to store, preserve, share, and analyse data in interoperable, sustainable, and trusted environments.

In other scientific disciplines, research data infrastructures (RDIs) have already become the backbone of collaboration and discovery. If archaeology is to keep pace with these developments, it must ensure that such infrastructures are **not only technically operational, but also widely adopted and embedded in everyday research practice**. Without this combination of functionality and uptake, archaeology risks falling behind in the wider scientific landscape.

This is particularly relevant to the CAA community, which thrives at the intersection of archaeology, computing, and quantitative analysis. The power of advanced methods—statistical modelling, machine learning, network analysis, and simulation—relies on having **large, well-curated, and accessible datasets**. Without robust infrastructures that enable aggregation,

interoperability, and reuse, the potential of these methods cannot be fully realised.

Across Europe, RDIs for archaeology exist at different stages of maturity:

- **Established services** with decades of experience in preservation and dissemination.
- **Mid-career infrastructures** that have proven their value and are scaling their operations.
- **New initiatives** still defining their scope, governance, and technical frameworks.

Understanding how these infrastructures develop, gain acceptance, and adapt is not just a matter of institutional interest—it is a prerequisite for archaeology to remain an evidence-driven, data-rich, and methodologically innovative discipline.

### Scope and Goals

This round table will bring together representatives from archaeological RDIs in different countries to exchange practical, experience-based perspectives. Our goals are to:

1. **Compare engagement models** — How do top-down institutional approaches differ from grassroots, community-driven models? How are archaeologists incentivised to contribute data? What roles do professional associations and informal networks play?
2. **Examine trust and acceptance** — What makes researchers, heritage professionals, and institutions actually choose and use an infrastructure? How do early-stage projects build credibility, and how do mature infrastructures sustain it?
3. **Share operational challenges and lessons learned** — Insights into technical deployment, training, support, funding continuity, and sustainability planning.

4. **Explore different stages of development** — How do priorities, risks, and opportunities change from the early phases to long-term operation? What can young initiatives learn from established ones, and how do established infrastructures stay agile?
5. **Analyse legal forms and frameworks** — How do organisational structures (federated vs. centralised, public bodies, consortia, non-profits, etc.) and differing national or EU legal environments affect governance, data policies, and the ability to collaborate internationally?

### Comparative Dimension

A central feature of this session is its explicitly comparative approach. By bringing together infrastructures that differ in **community size, governance model (federated vs. centralised), juristic form, funding environment, and stage of development**, we will highlight both common challenges and distinctive solutions. The discussion will not only compare archaeological infrastructures across national contexts but also set them in relation to established examples such as the **Archaeology Data Service (UK)**, community-driven organisations like **CAA International**, and interdisciplinary frameworks such as the **Research Data Alliance**. This comparative lens will ensure that the session moves beyond isolated case studies to identify transferable lessons, structural constraints, and opportunities for cross-disciplinary collaboration.

### Format and Structure

The round table will be structured for maximum interaction:

- **Opening statements:** Each panelist will have 5–7 minutes to introduce their infrastructure, national context, and position on the themes above.
- **Thematic discussion blocks:** The moderator will guide the conversation through the five key themes, drawing comparisons and encouraging panelists to reflect on successes, failures, and unexpected challenges.

- **Audience engagement:** Participants will be invited to contribute their own experiences, pose questions, and comment on the applicability of different approaches in their contexts.
- **Summary and recommendations:** The session will conclude with collaboratively defined takeaways, which will be documented and shared with the CAA community.

### Expected Audience

We expect this session to attract:

- Archaeologists and heritage professionals involved in data management or infrastructure projects.
- Members of the CAA community working with quantitative methods who depend on large, interoperable datasets.
- Policy makers, funders, and administrators concerned with digital research sustainability.
- Students and early-career researchers looking to understand and influence the future of archaeological data sharing.

### Relevance to CAA 2026

The CAA community is uniquely positioned to benefit from and contribute to the development of archaeological RDIs. This session addresses core concerns of the conference:

- **Advancing quantitative archaeology** by enabling large-scale, high-quality datasets for analysis.
- **Strengthening international collaboration** through shared infrastructure models and interoperability.
- **Bridging policy and practice** by comparing how national contexts and legal frameworks shape the reality of implementation.
- **Encouraging sustainable, community-driven solutions** for data preservation and access.

If archaeology is to continue evolving as a data-intensive science, it must ensure that RDIs are not just technically sound, but fully embedded in the discipline's workflows. This round table will directly address how to achieve that goal.

### Expected Outcomes

By the end of the session, participants will have:

- A comparative map of how archaeological RDIs operate in different legal, organisational, and community contexts.
- Insights into how infrastructure maturity shapes priorities and challenges.
- Practical strategies for fostering trust and adoption in digital services.
- A clearer understanding of the role infrastructures play in enabling large-scale quantitative methods in archaeology.
- A set of shared recommendations for the CAA community and beyond.

The discussion outcomes will be summarised and shared publicly after the conference in paper form, ensuring that insights reach practitioners who could not attend.



## S29: AI Across the Heritage Pipeline: From Algorithms through Fieldwork to Deliverables

Katherine Crawford, *Chronicle Heritage*

Tom Fitton, *Chronicle Heritage*

**Location:** Hörsaal 03

**Session Format:** Standard

Artificial Intelligence and Machine Learning are increasingly becoming core components in various subfields of archaeology, with potential applications in desk-based assessments, remote sensing, field recording, and 3D modelling (e.g. Landauer et al. 2025; Stoean et al. 2024; Küçükdemirci and Sarris 2022). Many of these applications remain disconnected, however, with limited awareness across given stakeholders of how these processes are applied and regulated (Gattiglia 2025; Griffin et al. 2024).

This session seeks to couple innovative use-cases of AI and ML with methodological rigor across the fields of archaeology, heritage studies, and cultural resource management. We intend to stimulate conversation and engagement on how we might consolidate best practices for AI/ML in archaeology by linking algorithmic/model innovation to measurable outcomes and transparent governance, advancing research applications that are scientifically robust, ethically responsible, and directly applicable to heritage management practices. We seek contributions that present new models, architecture, or evaluation frameworks, as well as papers that demonstrate how these methods can be embedded within end-to-end workflows and communicated to end-user audiences (Klein et al. 2025).

Recognizing that CRM and cultural heritage projects often rely on proprietary or sensitive datasets, we place particular emphasis on governance and reproducibility under contractual and confidentiality constraints. Developing guidelines and legislation such as the EU Artificial Intelligence Act are likely to result in archives and clients requiring transparent documentation, model

disclosure, and reproducible evaluation. We especially welcome contributions that translate these requirements into pragmatic workflows.

### Topics of interest:

- Scalable site/feature detection from LiDAR and optical imagery, optimizing false positives triage and ground truthing workflows.
- Multimodal fusions (e.g. LiDAR, historic maps, GIS layers) for improved detection and interpretation.
- Application of models for condition monitoring and compliance, from change detection to action thresholds.
- End-to-end AI pipelines including data acquisition, modelling, and client deliverables.
- Challenges or limitations of current AI tools within cultural heritage
- Governance for proprietary/sensitive data

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**08:30 – 08:50** 230. AI-Based Archaeological Site Prediction Using Community Archaeology Data  
*Gulyás András (Jász Múzeum); Hegyesi Viktor (Jász museum)*

**08:50 – 09:10** 308. Shipwreck detection in bathymetry data using semi-automated methods: Combining machine learning and topographic inference approaches  
*Cal Pols (University of Southampton)*

**09:10 – 09:30** 386. Linking Ground and Aerial Perspectives: A Vision-Based Workflow for Archaeological Surface Survey  
*Kyriakos Sgouropoulos (Democritus Univeristy of Thrace); Apostolos Sarris (University of Cyprus); Dushka Urem-Kotsou (Democritus Univeristy of Thrace)*

**09:30 – 09:50** 327. Unified Cross-Platform Workflow for Digital Twin Generation of Archaeological Monuments Using Universal Coded Markers

*Georgi Vasilev\*; Milen Borisov (Institute of Mathematics and Informatics - Bulgarian Academy of Sciences); Stanislav Harizanov\*; Miglena Raykovska\*; Lyubka Pashova (National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences, Geodesy); Pavel Georgiev\*; Nikolay Petkov\*; Georgi Evtimov\*; Tsvetan Ostromski\*; Svetlana Trifonova; Ivan Lirkov\**

*\* Institute of Information and Communication Technologies, Bulgarian Academy of Sciences*

**09:50 – 10:10** 325. Morphology-Aware Digital Frottage from 3D Scans: A Case Study on Workflow and Time Reduction  
*Keonwoo Lee (carrotphant. INC.), Hyunju Seo (carrotphant. INC); Dongseok Kang (Dongguk university)*

**10:10 – 10:30** 167. Revisiting Ancient Ceramic Production Chains: Contributions from Deep Learning  
*Thaïs Wuillemain (CNRS); Gabriel Ducret (IFPEN); Suzanne Bussod (IFPEN); Serge Cohen (IPANEMA UAR3461 - CNRS); François Giligny (Université Paris 1 Panthéon-Sorbonne); Maxime Moreaud (Manufacture Française des Pneumatiques Michelin, IFPEN); Louise Gomart (Trajectoires. De la sédentarisation à l'Etat UMR8215 – CNRS)*

**10:30 – 11:00** Coffee break

**11:00 – 11:20** 165. Bridging Data Gaps in Heritage Science with AI: Non-Destructive Ink Identification on Silk Painting via Synthetic Image Generation

*Sumiko Teng (Government Technology Agency); Sone Kyaw Pye (Government Technology Agency); Zijin Jiao\*; Lynn Chua\*; Shi Jie Lio\*; Siew Wah Lee\*; Hui Min Teo (National Gallery of Singapore)*

*\* Heritage Conservation Centre, National Heritage Board*

**11:20 – 11:40** 373. Feature Engineering and Machine Learning for the Objective Validation of Rock Art Chronologies: The Tagus Valley Case Study

*Sara Garcês\*; Sandra Jardim\*; Hipólito Collado (Instituto Terra e Memória); Hugo Gomes\*; Clerismar Mota\*; Dionysios Danelatos\*; Noélia Priego (Instituto Terra e Memória); Mahym Amanova (Instituto Terra e Memória); Luiz Oosterbeek\**

*\* Polytechnic Institute of Tomar*

**11:40 – 12:00** 128. Artificial Reconstruction: Exploring AI-assisted 3D Reconstruction of Archaeological Artefacts  
*Björk Kosir (University of Vienna)*

**12:00 – 12:20** 382. A Grid-Based AI System for Chromatic Reconstruction of the Feo Chapel Frescoes

*Alessia Remondini (Sapienza University of Rome); Paola Pisano (University of Turin)*

**12:20 – 12:40** 447. Safeguarding Azulejo Heritage: A Deep Learning Approach to Pathology Detection and Monitoring  
*Liane Lin\*; Mariana Santos\*; Sara Pires\*; António Antunes\*; Gonçalo Jesus\*; Dora Roque\*; Marluci*

*Menezes\*; Lurdes Esteves (National Tile Museum); Anabela Oliveira\*; José Machado\*; Sílvia Pereira\**

*\* National Laboratory for Civil Engineering*

**12.40 – 13:00** 332. A Multimodal Continual Learning for Adaptive Heritage Building Degradation Prediction  
*David Roqui (ETIS/C2RMF)*

## 128. Artificial Reconstruction: Exploring AI-assisted 3D Reconstruction of Archaeological Artefacts

*Björk Kosir (University of Vienna)*

### Introduction

Reconstructions of the past have long fascinated people, especially when the physical remains of sites, buildings or artefacts are only partially preserved or lost entirely. Such reconstructions can help to visualise the past and serve research, museum exhibitions and educational purpose. Archaeological reconstruction exists in two forms: analogue (traditional drawings and hand-built models) and digital (3D models and digital drawings). Digital reconstruction, particularly through computer modelling, goes beyond simple digitisation by incorporating and integrating historical sources and interpretation into the modelling process. A digital 3D reconstruction functions as a three-dimensional information model, allowing for potential multiple interpretative trials. Despite its advantages, traditional reconstruction methods remain time-consuming and costly. As AI increasingly enters the field of archaeology, its integration into digital workflows is expending. However, the use of AI-assisted tools for digital 3D reconstruction is still in its early stages. Therefore, this paper explores how existing AI tools can enhance the efficiency and accuracy of three-dimensional reconstructions in archaeological artefacts

and whether AI-based reconstructions carry different or further interpretative implications compared to solely human-made reconstructions.

## Methods and materials

This paper proposes a potential AI-assisted reconstruction workflow that incorporates tools from three methodological categories: (1) a manual approach, (2) a generative AI approach and (3) a deep learning approach. The integration of these three categories enables a seamless workflow with satisfactory reconstruction results. This approach is demonstrated on two ceramic use cases: a contemporary conical shaped vase and a medieval bowl from the 14th century.

(1) The objects in question were first digitised as 3D models by using the photogrammetry software Agisoft Metashape, which provides not only geometry and texture, but also metadata such as point density for comparison with the reconstruction outputs.

(2) A semi-automated modelling process was carried out to generate ground-truth models using a MCP (Model Context Protocol) in combination with ChatGPT model 5 and Claude model Sonnet 4, integrated into the modelling software Blender, for prompt-based 3D modelling, where LLM-generated geometry suggestions were followed by manual refinement to ensure geometric accuracy and plausibility.

(3) PCN (Point Completion Network), a deep learning model with an encoder-decoder architecture, which combines two MLPs (Multi-Layer Perceptrons) was employed (Yuan et al. 2019). The trainings dataset included the preserved 3D model, the ground-truth reconstruction and at least three additional reference models of similar shape and size to generate a point cloud reconstruction.

The additional data of similar shaped and sized 3D models for training were sourced from the platform Sketchfab, licenced under a CC-BY 4.0. This approach proved especially suitable for archaeological

artifacts as for the two use cases only a few supplementary trainings datasets were required to achieve satisfactory outputs for further processing.

## Results

The combined usage of the three approaches highlights their respective performance and potential. For both use cases, the manual approach produces precise outputs of the preserved object state, suitable for further processing. The GenAI-based output varied depending on the object's shape and complexity, as well as the chosen LLM used with the MCP Blender pipeline. Some human intervention remained necessary to produce the ground-truth models, as well as additional manual work to apply textures which were captured during the photogrammetry stage. The deep learning approach for the point cloud reconstruction produced satisfactory results, defined as outputs that preserved the overall shape of the object, accurately fitted observed breakages and retained sufficient point density for further processing. The output quality depended on the availability of similar reference 3D models and was influenced by code parameters, particularly the number of reconstructed points, as a denser reconstruction yielded more detailed models. Additional factors, such as scaling, normalisation and object positioning during training and the reconstruction process, also affected the results. For both use cases, using five reference models, including the preserved state, produced satisfactory outputs in terms of shape and breakage fitting, although the small training set may limit generalisation. Since PCN outputs are point clouds, further processing in Blender or other software is required for mesh generation, texturing or comparative analysis.

## Discussion

Archaeology as a discipline is still in the post-digital era, but not yet in a post-AI (Gattiglia 2025, 231). The approach presented in this paper demonstrates, while AI tools, such as integrated GenAI systems and deep learning models can enable a faster and more collaborative digital reconstruction process, they also introduce new interpretative dimensions. AI-assisted reconstructions can reduce certain biases and reveal hidden patterns in the reconstruction process, yet they may also lack transparency. Therefore, detailed documentation from the harvesting of the trainings data to the final output is essential for traceability. AI tools are not yet fully autonomous, as they require continuous human-in-the-loop integration and expert review. Consequently, AI-assisted reconstruction should be viewed not a replacement for human interpretation, but as an extension of it. A process that expands interpretative possibilities while demanding critical evaluation.

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#### 165. Bridging Data Gaps in Heritage Science with AI: Non-Destructive Ink Identification on Silk Painting via Synthetic Image Generation

*Sumiko Teng (Government Technology Agency)*

*Sone Kyaw Pye (Government Technology Agency)*

*Zijin Jiao (Heritage Conservation Centre, National Heritage Board)*

*Lynn Chua (Heritage Conservation Centre, National Heritage Board)*

*Shi Jie Lio (Heritage Conservation Centre, National Heritage Board)*

*Siew Wah Lee (Heritage Conservation Centre, National Heritage Board)*

*Hui Min Teo (National Gallery of Singapore)*

Ink identification on paper-based artworks presents technical challenges to conventional chemical analysis, particularly due to the minute quantity of ink, the difficulty of separating it from the fibre substrate and similarities in ink-matrix compositions (López-Baldero 2025; Swider et al. 2003). Sampling is often restricted because of the artwork's pristine condition. These challenges are exemplified in the analytical investigation of *Drying Salted Fish* (1978) by artist Cheong Soo Pieng, executed with ink on sized silk mounted on paper. Cheong, known for his distinctive synthesis of easel painting and Chinese ink traditions, was highly deliberate in his choice of materials – especially ink selection - which is central to interpreting his oeuvre. The need to understand the ink composition in this work therefore provided the impetus to develop a non-destructive method for ink identification in artworks.

Mock-ups replicating the construction of the painting were prepared using different ink types (inkstick, liquid ink and watercolour), from which a microscopic image dataset was established to examine their morphological characteristics. Visual inspection revealed certain distinctions between the ink classes; however, this process is limited by the scarcity of reference datasets from historical paintings and potential human bias. To overcome their constraints, we explore the use of AI-driven image classification and a synthetic data generation approach to enhance the accuracy, consistency and objectivity of ink identification in this study.

Three 500X magnification microscopic image datasets spanning different historical periods were collected for this study. A modern ink dataset consisting of contemporary ink mock-ups (artificially created), an ancient ink dataset from two paintings with known ink compositions: Poem in Running Script by Zhang Ruitu (late 16th–mid 17th century) and Landscape in the Style of Huang Gongwang by Yuanqi Wang (1711) and the unknown dataset comprising of microscopic images from Drying Salted Fish (1978) by artist Cheong Soo Pieng. Parts of this unknown dataset were manually labelled through close inspection of the ink characteristics observed in the microscopic images.

To evaluate cross-temporal generalizability, image classification ResNet-50 (He et al. 2015) model was trained using the modern ink dataset and subsequently tested on the ancient ink dataset to assess whether models trained on contemporary samples could accurately identify inks from earlier centuries.

The second part of this study adopted a synthetic data generation approach based solely on the Drying Salted Fish dataset. Given the limited number of manually labelled images, the descriptive annotations provided by human labellers were used to fine-tune the Flux Dev 1 text-to-image model using LoRA. This fine-tuned model was then employed to generate additional synthetic microscopic ink images resembling those ground truth dataset. The resulting synthetic dataset was subsequently integrated into the ResNet-50 training process, allowing the ResNet-50 model to learn ink characteristics

specific to the Drying Salted Fish painting. These models were then evaluated on the real microscopic ink images to determine their ability to identify ink regions when being trained with only synthetic data.

The results of the first set of experiments revealed poor cross-temporal transferability. When the model trained on modern ink data was tested on ancient samples, the ResNet-50 architecture achieved only an F1 score of 1.20%, indicating that models trained on inks from one era fail to generalize to those from significantly different time periods. In contrast, the synthetic data approach proved highly effective. Using only a small number of manually labelled images for fine-tuning, the ResNet-50 model achieved an F1 score of 92.53% when trained on the synthetically generated dataset and tested on real images. These findings demonstrate that ink samples from different historical periods cannot be used interchangeably for accurate classification; however, by generating synthetic data aligned with the same temporal and stylistic domain, it is possible to mitigate data scarcity and achieve strong classification performance in non-destructive ink analysis.

The results demonstrate the importance of selecting an appropriate training dataset to develop a robust model. By using data derived directly from the artwork under investigation - rather than relying solely on mock-ups or artworks from different periods or artists – and by generating synthetic data to mitigate data scarcity, the model's performance was significantly improved. This approach presents a viable AI-assisted tool to support human visual assessment in ink identification. The collaboration between Heritage Science and Artificial Intelligence highlights how AI-driven image analysis can effectively distinguish different ink types on silk paintings, contributing to the advancement of non-destructive methodologies for the material analysis of artworks.

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## 167. Revisiting Ancient Ceramic Production Chains: Contributions from Deep Learning

*Thaïs Wullemmin (CNRS)*

*Gabriel Ducret (IFPEN)*

*Suzanne Bussod (IFPEN)*

*Serge Cohen (IPANEMA UAR3461 - CNRS)*

*François Giligny (Université Paris 1 Panthéon-Sorbonne)*

*Maxime Moreaud (Manufacture Française des Pneumatiques Michelin, IFPEN)*

*Louise Gomart (Trajectoires. De la sédentarisation à l'Etat UMR8215 – CNRS)*

Ceramics are among the very first artificially created materials, and their technical traditions have developed through the accumulated practices and knowledge of human communities over thousands of years. Today, ancient ceramics are almost systematically found in archaeological excavations and provide a remarkably rich record on past societies.

Ceramic technology, as an archaeological field, aims to reconstruct the chaîne opératoire behind pottery production, offering crucial insights into past human societies, organization, trajectories and interactions. Within this framework, the forming method is a particularly stable step in the manufacturing sequence, often persisting in a community of practice and serving as a strong indicator of social boundaries. As the gestures involved in forming leave characteristic traces on archaeological ceramics, forming methods can be inferred from a range of clues, such as surface topography, fracture patterns, or the organization of pores and inclusions within the clay matrix. However, these traces tend to be tenuous and conventional analyses rely on experts' visual observation, limited to surfaces, cross-sections of the ceramics, or thin sections obtained through destructive analysis.

The ability to visualize the internal structures of archaeological ceramics non-destructively has long been a major methodological challenge. The development of X-ray microtomography in the late 20th century radically transformed this situation by enabling the 3D visualization of internal microstructures at micrometric resolution. This technique opens new possibilities to directly observing the volumetric signatures of forming gestures within the clay matrix [1]. Yet, moving from traditional 2D observation to 3D volumetric analysis raises new methodological questions: how can one define and interpret 3D traces of forming techniques when no direct reference exists? Addressing this requires the establishment of a new 3D reference dictionary of forming methods, a foundational step toward the systematic and reproducible classification of archaeological ceramics based on their internal structure. At the same time, microtomography generates extremely large and complex datasets that exceed the capacity of traditional archaeological analytical tools. In many other disciplines where microtomography is widely used, such as materials science, geoscience, or dentistry, this challenge has been addressed through the implementation of deep learning, and in particular Convolutional Neural Networks (CNNs)

CNNs enable robust and objective image segmentation and classification, often matching or surpassing human performance in detecting fine details. Applied to ancient ceramic sherds, they provide powerful tools for identifying

forming methods. The CERAJUM project (2024–2027) leverages this potential by uniting archaeologists and data scientists to combine advances in computer vision with expertise in ceramic chaîne opératoire and technical traditions. Beyond methodological innovation, it aims to establish a 3D reference framework for early European pottery, supporting cross-cultural and diachronic comparisons.

As a case study, the project focuses on the early Neolithic ceramics of the Aisne Valley (Picardy, France), a key region in the processes of neolithization in northwestern Europe. The valley was a crossroads of interactions, exchanges, and migrations between several communities with distinct cultural and technological traditions. Its ceramic assemblages reflect this diversity, making it an ideal context to explore variability in forming techniques.

To establish a robust dataset for the training of deep models, CERAJUM combines archaeological and experimental materials. A total of ten identified archaeological sherds and eighteen experimental sherds were selected to train models for semantic segmentation and classification tasks. More specifically, U-net-type architectures will be used for segmentation tasks [2], and vision transformer-type architectures will be used for classification tasks [3], combined with data augmentations techniques adapted for 3D data. The samples were scanned in 2024 at the Synchrotron Soleil facility, using high-energy X-ray beams to obtain volumetric data at a resolution of 7  $\mu\text{m}$ . The resulting 28 tomographic volumes provide unprecedented insights into the inner architecture of ceramic sherds, capturing the fine organization of pores, inclusions produced by different forming gestures. Preliminary results present the initial labeled corpus, on which every following analysis will draw. In order to train models that will segment voids, or categorize zones of the volumes according to forming techniques, it is critical to annotate the data in a way that incorporates the archaeological knowledge of the corpus and of past practices, insuring the selection of appropriate representative technical gestures, pores and fractures of interest. This specific continuous interaction between disciplines entirely enables this project, ensuring that algorithmic decisions remain anchored in archaeological reasoning.

By combining microtomography and deep learning, the project introduces a new methodological paradigm for ceramic studies: a volumetric, quantitative, and reproducible approach to the analysis of forming gestures. It exemplifies how interdisciplinary collaboration can transform the study of ancient technologies, providing both enhanced analytical capacities and a deeper understanding of human technical behavior.

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## 230. AI-Based Archaeological Site Prediction Using Community Archaeology Data

*Gulyás András (Jász Múzeum)*

*Hegyesi Viktor (Jász Múzeum)*

#### Introduction

This paper presents an AI-supported archaeological site prediction and monitoring system that integrates community-generated metal-detecting data with spatial analysis and machine-learning-based anomaly detection. Predictive modelling and spatial pattern recognition have long been central to computational archaeology; however, their operational integration into field-work planning and heritage management remains uneven, particularly when non-traditional data sources are involved. The system presented here was developed within a long-term community archaeology programme with the explicit aim of transforming volunteer observations into analytically robust inputs for archaeological research and heritage protection, while maintaining methodological transparency, professional oversight, and ethical data governance.

Volunteer records are ingested as point observations with 16 structured fields, comprising (i) spatial-temporal metadata (coordinates, timestamp, recorder pseudonym, and survey-effort proxies), (ii) find descriptors (object category or type, material, and chronological attribution where available), and (iii) media documentation (geotagged photographs). For modelling purposes, these data are used to construct spatio-temporal event series, to stratify analyses by artefact categories (e.g. coin versus non-coin finds), and to derive environmental covariates at each observation point, including DEM-based terrain derivatives, hydrographic distance metrics, and aerial-archaeological layers. By explicitly defining how community-generated data enter the analytical pipeline, the approach directly addresses recurring concerns within AI-assisted archaeology regarding black-box modelling and interpretability.

The system was developed by the Jász Museum as part of Hungary's first large-scale community archaeology initiative explicitly designed to support the analytical reuse of metal-detecting data. Using a mobile field application, contributors systematically record find-related information under a controlled data model. While several European initiatives exist—most notably the UK Portable Antiquities Scheme and Denmark's DIME project (Dobat and Jensen 2016; European Public Finds Recording Network 2024)—these primarily focus on documentation, archiving, and public reporting. In contrast,

the present approach extends community data use toward AI-assisted site prediction and the monitoring of metal-detecting activity, embedding citizen-generated observations within an operational analytical workflow that directly supports archaeological interpretation and heritage management decision-making.

## Methods and Materials

The predictive workflow integrates volunteer-recorded find data with Copernicus digital elevation models, hydrography, and aerial archaeological datasets within a GIS-based analytical environment. Prior to analysis, records undergo data cleaning, typological harmonisation, and spatial validation to ensure internal consistency and analytical usability. Both positive observations (find locations) and negative survey information (surveyed areas without recorded finds) are retained. This design choice directly addresses well-documented sampling and reporting biases in public finds datasets, where the absence of data is often unrecorded, leading to distorted spatial interpretations (Robbins 2012).

Spatial clustering is performed using DBSCAN to identify find concentrations and settlement-like structures based on point proximity and density. Kernel density estimation (KDE) is applied to generate continuous intensity surfaces that visualise gradients in archaeological potential and survey activity, following established practices in archaeological spatial analysis (Baxter 1997). Anomaly detection operates on behavioural and recording features—including visit frequency, revisit intervals, spatial dispersion, category mix, and metadata completeness—using Fisher's exact test for categorical contrasts and Isolation Forest for multivariate outlier detection. Together, these methods combine unsupervised spatial pattern recognition with machine-learning-based monitoring of recording behaviour.

Rather than producing binary site/non-site classifications, model outputs are expressed as probabilistic hotspot and intensity surfaces. This probabilistic framing explicitly communicates uncertainty and avoids the false precision often associated with categorical prediction. The analytical pipeline produces georeferenced maps, a PDF and DOCX analytical report, and

GeoPackage (GPKG) datasets suitable for further GIS-based analysis, field survey planning, and heritage-management workflows.

## Results

Preliminary testing in the Jászág region demonstrates a strong correspondence between model-identified hotspots and previously verified archaeological sites, indicating that the integration of community-generated data with spatial analysis can successfully highlight zones of elevated archaeological potential. The inclusion of negative survey information and survey-effort proxies improves model robustness by reducing the overemphasis on intensively visited areas, a common limitation of presence-only datasets.

Continuous input from community archaeologists incrementally enhances spatial coverage and model performance over time. Anomaly detection identifies atypical recording or activity patterns that may signal methodological issues, unusual survey behaviour, or heritage-management concerns requiring professional attention. These results demonstrate that systematically structured community archaeology data can meaningfully enhance spatial pattern recognition and archaeological potential mapping when embedded within a transparent and critically designed analytical framework.

## Discussion

Beyond technical performance, the project addresses key epistemological and ethical questions associated with AI-supported analysis of community-generated archaeological data. By retaining both presence and absence information, explicitly modelling survey effort, and avoiding opaque predictive outputs, the system responds to long-standing critiques of predictive modelling in archaeology related to bias, interpretability, and overconfidence. In this context, “prediction” is understood not as deterministic site discovery, but as data-driven potential mapping that supports informed decision-making in archaeological practice.

The integration of community participation into this workflow does not diminish professional control; rather, it extends archaeological expertise through structured collaboration. Access control mechanisms and

aggregation strategies are implemented at the analytical level to prevent the inappropriate dissemination of sensitive location data, aligning the system with emerging best practices in digital heritage ethics and responsible data governance.

Overall, this contribution positions AI not as a replacement for archaeological expertise, but as an integrative tool linking community participation, spatial analysis, and heritage deliverables within a single pipeline. By clearly documenting what data enter the system, how they are transformed, and how outputs are interpreted, the paper responds directly to calls within the CAA community for methodological transparency and socially grounded computational archaeology. The approach presented here offers a transferable model for responsibly embedding AI-supported analysis within community-based archaeological research and heritage protection strategies.

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**308. Shipwreck detection in bathymetry data using semi-automated methods: Combining machine learning and topographic inference approaches**

*Cal Pols (University of Southampton)*

This research presents a semi-automated workflow that integrates machine learning methods with geospatial data analysis to improve the identification and characterization of shipwrecks in bathymetry (seabed elevation) data. By first refining the study area into high-potential units, machine learning algorithms can be applied more efficiently. This approach accelerates the process, reduces computational demands, and offers an adaptive method that can be tailored to survey needs and different seabed environments.

The developed workflow uses a raster extraction method as a filtering process to identify areas of seabed with high shipwreck potential, based on their topographic signature in three different visualisations of bathymetry (slope, curvature, and topographic position index). Using these results, several different machine learning algorithms were tested on their ability to identify both intact, visible shipwrecks ('conspicuous' wrecks) as well as smaller, possible wreck sites. These methods were tested over an area of 3,131 km<sup>2</sup> from the south coast of England.

This paper contributes to the current discourse surrounding the discovery and management of underwater cultural heritage (UCH) in the context of global seabed mapping, developments in autonomous marine survey, and continued offshore development. Shipwrecks constitute a significant proportion of UCH sites that are increasingly likely to be discovered and impacted by these developments, and thus archaeologists need adequate tools for their rapid detection and monitoring to keep pace with the rate of data generation.

### 325. Morphology-Aware Digital Frottage from 3D Scans: A Case Study on Workflow and Time Reduction

*Keonwoo Lee (carrotphant. INC.)*

*Hyunju Seo (carrotphant. INC)*

*Dongseok Kang (Dongguk university)*

"Frottage" is a long-standing method for recording the surface information of artefacts and underpins a wide range of archaeological research. However, physical frottage is vulnerable to environmental factors such as humidity, contamination, and material degradation, so there is a practical need for robust digital alternatives. Prior efforts have used 3D scans and shading-based visualisations (e.g., ambient-occlusion-style maps) to produce images that resemble frottage. These approaches capture gross relief but often fail on objects with irregular or mixed morphology, where a single uniform operator either over-enhances sharp rims or washes out broad, shallow features. Critically, for many artefacts the perceptual boundary between "convex" and "concave" is not crisply defined at a single geometric threshold; expert frottage practice instead reflects contextual, scale-dependent judgement. This motivates a data-driven model that can learn how relief cues map to stable black/white tonal decisions.

This work presents a morphology-aware pipeline for generating digital frottage directly from 3D scan data, combining explicit geometric cues with supervised learning from expert-produced references. We first compute view-dependent depth-derived signals on the scan (normalised depth, depth gradients, and curvature-proxy descriptors) to capture local slope changes and multi-scale relief strength. These signals are then assembled as a multi-channel 2D representation under a controlled projection, forming a consistent input for learning and downstream rendering. On this representation, we train a lightweight conditional U-Net to predict a frottage tonal field that emulates human rubbing: the network maps the depth/gradient/curvature channels to a grayscale "frottage backbone" and is supervised by paired data consisting of (i) artefact 3D scans and (ii) human-made frottage outputs treated as ground truth. Architecturally, the U-Net uses an encoder-decoder with skip connections to preserve fine edges while capturing broader relief context; training optimises a composite objective that combines intensity fidelity (e.g., L1), structure preservation (SSIM), and an edge-aware term to

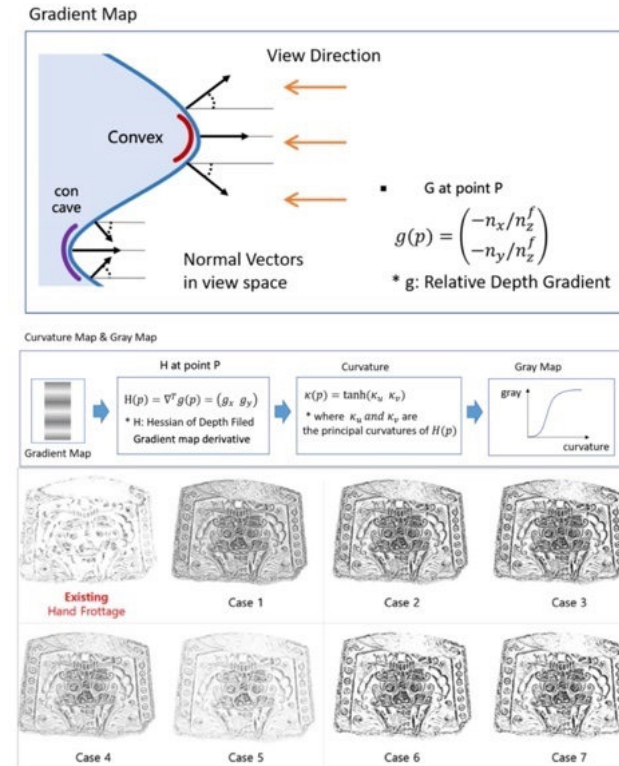
encourage sharp, interpretable boundaries without haloing. At inference time, the model produces a stable tonal backbone that is subsequently refined with conservative, edge-preserving smoothing and contrast shaping to suppress ringing and over-sharpening artefacts common in uniform pipelines. The overall workflow remains parameter-light for end users, while replacing hand-crafted routing with learned, expert-aligned tonal decisions.

Evaluation combined structured benchmarking with expert review across multiple artefact typologies. In a standardised setting the pipeline achieved an average processing time of 23 minutes per artefact, yielding approximately eight-fold throughput over conventional manual workflows without sacrificing interpretive quality. In a 100-item blind assessment by heritage specialists, more than 98 items met the acceptance criterion for interpretive usability, with reviewers noting that the outputs consistently emulate expert-level line placement and representational choices; some cases still benefited from user selection among multiple candidate renderings, positioning the method as decision support rather than a fully autonomous replacement. We further contrasted our approach with three common baselines—(1) uniform curvature-style shading, (2) gradient-only edge maps, and (3) ambient-occlusion-style shading—where baselines either over-emphasised sharp rims or obscured shallow relief, while our learned tonal mapping preserved low-relief readability and reduced artefacts across diverse materials and manufacturing techniques.

Typical failure modes involve noisy scans with irregular triangulation, extremely shallow relief under poor illumination, and surfaces dominated by texture rather than geometry. We mitigate these with mesh-quality checks, adaptive smoothing bounds, conservative contrast in saturated regions, and optional re-selection of view direction for problematic patches.

Our contributions are threefold: (1) a scan-informed, morphology-adaptive digital frottage pipeline that couples geometric analysis with a learned tonal predictor; (2) a paired-data training protocol and compact operator toolkit

that generalises across artefact types; and (3) empirical evidence of substantial time savings with expert-validated interpretive reliability. The workflow aligns with FAIR practices; upon acceptance we plan to release an anonymised example dataset, parameter presets, and a minimal script bundle that reproduces key figures. For field and museum contexts, the method offers a practical route to produce consistent, legible frottage-style outputs in minutes rather than hours, and it integrates cleanly with downstream tasks such as semi-automated measured drawing and comparative analysis.





## 327. Unified Cross-Platform Workflow for Digital Twin Generation of Archaeological Monuments Using Universal Coded Markers

*Georgi Vasilev (Institute of Information and Communication Technologies)*

*Milen Borisov (Institute of Mathematics and Informatics - Bulgarian Academy of Sciences)*

*Stanislav Harizanov (Institute of Information and Communication Technologies)*

*Miglena Raykovska (Institute of Information and Communication Technologies)*

*Lyubka Pashova (National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences, Geodesy)*

*Pavel Georgiev (Institute of Information and Communication Technologies)*

*Nikolay Petkov (Institute of Information and Communication Technologies)*

*Georgi Evtimov (Institute of Information and Communication Technologies)*

*Tsvetan Ostromski (Institute of Information and Communication Technologies)*

*Svetlana Trifonova*

*Ivan Lirkov (Institute of Information and Communication Technologies)*

### Introduction

The creation of accurate and sustainable digital twins of archaeological immovable monuments has become one of the most transformative developments in digital heritage research over the past decade. As high-fidelity, metrically precise 3D representations of cultural heritage assets, digital twins are increasingly critical for the documentation, monitoring and conservation of vulnerable structures (Konstantakis et al. 2024). Despite significant advances in photogrammetry, LiDAR and laser-scanning technologies, the field still faces a persistent challenge (Guarnieri et al. 2004), which is achieving cross-

platform metric consistency and spatial interoperability between datasets. Divergences between sensor modalities, acquisition geometries and proprietary processing pipelines often lead to misalignments that undermine the scientific reliability, reusability and comparability of 3D heritage data. A fundamental cause of this issue lies in the use of Ground Control Points (GCPs) and coded markers - fixed spatial references essential for scaling, orienting and co-registering data from multiple sources. However, most current marker systems are proprietary and non-interoperable, as each photogrammetry or laser-scanning software (e.g., AliceVision Meshroom, Leica Cyclone, FARO Scene and other commercial photogrammetry software) employs its own marker detection algorithm and code geometry. This fragmentation constrains reproducibility and integration, particularly in complex multi-platform projects that combine aerial imagery, terrestrial photogrammetry and terrestrial laser scanning (TLS). For archaeological immovable monuments with eroded or featureless surfaces, these constraints critically impede precise georeferencing and long-term structural monitoring. The outcomes of a research initiative focused on developing an integral approach to creating digital twins of archaeological immovable monuments using innovative technologies are presented. An open, interoperable framework for digital twin creation is proposed, centered on the development of a universal coded marker system designed to ensure robust cross-platform detection, georeferencing, and alignment across diverse acquisition environments.

### Methods and Materials

The research adopted a multi-phase methodology integrating marker design, laboratory evaluation, field validation and integration into Heritage Building Information Modeling (HBIM) environments.

#### 1. Marker Design and Prototyping

The framework unifies all stages of marker utilization - from design and generation to recognition, coordinate transformation and data export, ensuring interoperability between different 3D reconstruction platforms. A universal coded marker set was developed to provide consistent spatial referencing and cross-platform compatibility across photogrammetry and TLS datasets.

## 2. Workflow Phases

The methodological workflow comprises four interlinked phases:

1. **Marker Design and Generation:** Universal coded targets were generated through a parametric, template-based approach, enabling scalable performance across variable imaging conditions and marker sizes.

2. **Image Acquisition and Recognition:** Automated algorithms detected and decoded markers, employing robust binarization and geometric validation for reliable recognition.

### 3. Data Transformation and Standardization

Detected marker coordinates were mapped into a unified reference frame, ensuring consistent alignment across photogrammetric, TLS and other 3D imaging modalities.

### 4. Cross-Platform Export and Integration

Standardized outputs were provided in open data formats compatible with external photogrammetric software, facilitating downstream documentation workflows and HBIM integration.

## Data Integration and Application

All spatial data were standardized within a unified coordinate framework using custom Python-based workflows implemented through a photogrammetry target toolkit. As part of this initiative, both the Human Readable Coded Targets (HRCTs) and the photogrammetry target toolkit workflow were developed to streamline marker management throughout the photogrammetric process. The toolkit automated the detection and extraction of HRCT locations from image datasets, generating structured CSV outputs directly importable into photogrammetric software. Through this process, marker positions and spatial references were efficiently synchronized across image sets, ensuring high positional accuracy and consistency. The resulting 3D datasets were subsequently integrated into HBIM systems, enabling cross-temporal alignment of multi-epoch surveys. This integration facilitated advanced spatial analyses for conservation planning, deformation monitoring, and the creation of sustainable digital twins, demonstrating the workflow's scalability and long-term applicability for heritage documentation and management.

## Data Acquisition and Processing

Data acquisition was conducted using high-resolution DSLR, UAV-mounted cameras and terrestrial laser scanners, capturing archaeological structures under both controlled laboratory and field conditions. The resulting datasets were processed through a combination of software like Leica Cyclone, FARO Scene and other commercial photogrammetry software, and open-source platforms like AliceVision Meshroom to evaluate geometric consistency and marker recognition accuracy.

## Results

The proposed framework demonstrated significant improvements in cross-platform registration accuracy and interoperability. Laboratory and field testing confirmed that the newly designed markers maintained stable centroid detection across wide angular ranges and variable imaging resolutions. Field validation further confirmed the system's robustness under challenging site conditions, including uneven lighting and irregular surfaces. The universal marker system enabled seamless co-registration between photogrammetric and TLS datasets without the need for software-specific conversions or manual alignment. Integration within HBIM environments further demonstrated the framework's potential for cross-temporal monitoring, as successive 3D models of test monuments were aligned within a unified spatial reference, enabling accurate visualization of structural deformations and material deterioration over time. To support these outcomes, the data processing pipeline was executed using the photogrammetry target toolkit, which automated human readable coded targets detection, coordinate extraction, and data standardization. Figure 1 illustrates the photogrammetry target toolkit's workflow, detailing the stages from image-based target extraction to CSV export and integration within 3D photogrammetric and HBIM environments.

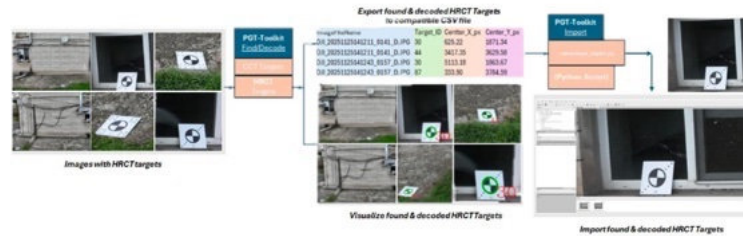


Figure 1. Photogrammetry target toolkit workflow diagram

## Discussion

The results confirm that embedding a universal coded marker system within an automated recognition and transformation pipeline provides a viable solution to one of digital heritage’s most persistent challenges - cross-platform spatial interoperability. By replacing proprietary, non-interoperable marker systems with an open, standardized solution, the proposed framework supports reproducible and scalable 3D documentation workflows, fostering collaboration across institutions and disciplines. Beyond technical interoperability, the integration within HBIM environments positions digital twins as dynamic, evolving records rather than static 3D models. This paradigm enables long-term conservation monitoring, deformation analysis, and collaborative planning across temporal documentation campaigns. The proposed approach aligns with the broader movement toward open science and standardization in computational archaeology, offering a practical pathway toward scientifically rigorous, sustainable digital twin generation. By addressing the core issue of metric interoperability, this project enhances the accuracy, transparency, and long-term scientific value of digital heritage documentation. (Haibt et al. 2024).

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## 332. A Multimodal Continual Learning for Adaptive Heritage Building Degradation Prediction

David Roqui (ETIS/C2RMF)

Heritage building preservation requires long-term monitoring systems capable of adapting to evolving degradation patterns across multiple temporal campaigns. Traditional deep learning approaches suffer from catastrophic forgetting when sequentially trained on data from different monitoring periods, limiting their applicability for multi-year heritage surveillance programs. We propose ComplementarityMoE, a continual learning framework designed for multimodal heritage monitoring that combines visual inspection imagery and sensor measurements. Unlike existing approaches that assign experts based on temporal campaign identity, our method uses Barlow Twins correlation analysis to route samples based on multimodal complementarity enabling the system to discover natural groupings in degradation patterns rather than arbitrary temporal divisions.

We validate our approach on three French heritage sites under active monitoring: Strasbourg Cathedral, Cocteau Chapel (Nice), and the Bibracte

archaeological site, using data from multiple temporal campaigns spanning several years. By leveraging Parameter-Efficient Fine-Tuning through LoRA, our architecture maintains computational efficiency suitable for heritage institutions with limited resources. Results on CMU-MOSEI benchmark demonstrate that complementarity-driven routing achieves competitive accuracy while reducing knowledge forgetting.

Our framework enables heritage professionals to continuously update monitoring models as new survey data becomes available, without losing predictive capability on earlier campaigns, a critical requirement for multi-decadal preservation programs. This work bridges advanced multimodal continual learning with practical cultural heritage preservation needs.

### 373. Feature Engineering and Machine Learning for the Objective Validation of Rock Art Chronologies: The Tagus Valley Case Study

*Sara Garcês (Polytechnic Institute of Tomar)*

*Sandra Jardim (Polytechnic Institute of Tomar)*

*Hipólito Collado (Instituto Terra e Memória)*

*Hugo Gomes (Polytechnic Institute of Tomar)*

*Clerismar Mota (Polytechnic Institute of Tomar)*

*Dionysios Danelatos (Polytechnic Institute of Tomar)*

*Noélia Priego (Instituto Terra e Memória)*

*Mahym Amanova (Instituto Terra e Memória)*

*Luiz Oosterbeek (Polytechnic Institute of Tomar)*

#### Introduction and Motivation

Rock art represents a vital component of global cultural heritage, offering insights into prehistoric symbolic expression and the evolution of human cognition and behavior. However, research in this field still relies heavily on comparative stylistic analysis, integrating typological, technical, and aesthetic assessments to establish cultural and chronological frameworks. In contexts where direct dating of engravings or paintings is not feasible, stylistic comparison remains the principal method for constructing relative chronologies.

The Tagus Valley Rock Art Complex in central Portugal exemplifies this challenge. Its extensive chronological framework, derived from stylistic, technical, and typological analysis of roughly 7,000 documented engravings, provides a key case study. First identified in the early 1970s, the complex is among the largest concentrations of rock art in the Iberian Peninsula. Although many engraved rocks were later submerged following dam construction, researchers managed to document the assemblage in detail (Garcês, 2017).

The rock art of the Tagus Valley reveals a long and diverse chronology. Evidence includes Palaeolithic-style engravings, animal representations attributed to the Mesolithic pre-schematic period, and geometric and abstract figures integrated into the schematic tradition of the Iberian Peninsula, dating from the Neolithic to the Bronze Age.

The classification of animal figures whose chronology lies between the end of the Palaeolithic and the beginning of the Neolithic has been particularly complex due to limited comparative material and the absence of clear stylistic or typological references. To address this, researchers analyzed figure superpositions between different chronological layers and compared them with rare parallels elsewhere in the Iberian Peninsula. This work identified a continuum of animal representations showing varying degrees of formal elaboration: some naturalistic, approaching Palaeolithic models, and others more schematic, with simplified forms and reduced anatomical detail.

Consequently, the more naturalistic examples were associated with earlier artistic traditions linked to Palaeolithic hunter-gatherers, while the more schematic examples were interpreted as works of late Holocene hunter-gatherers, anticipating the schematic art of the Neolithic. Nonetheless, this hypothesis of formal evolution during the early Holocene remains based largely on subjective stylistic judgments and empirical observation.

The aim of the present study was to test the validity of this proposed formal evolution in animal representation using an objective, quantitative, and reproducible analytical framework.

#### AI Methodology: Quantitative Analysis of Formal Evolution

To reduce subjectivity in stylistic comparison and evaluate the archaeological hypothesis, this study employed a quantitative, data-driven approach using Artificial Intelligence (AI), integrating Computer Vision and Feature Engineering techniques (Jalandoni et al., 2022).

The input data consisted of digital documentation from the Tagus Valley Rock Art Complex, focusing on pre-schematic animal figures. High-resolution digital tracings were converted into binary image masks to standardize the dataset and eliminate background variation. Each figure was then normalized for scale, translation, and rotation, ensuring that the computational models learned stylistic rather than incidental visual variation.

Feature Engineering extracted objective descriptors aligned with archaeological concepts of formal elaboration and schematism. Shape complexity was quantified using the Perimeter–Area Ratio, where higher values indicated greater detail and naturalism, and the Shape Factor or Compactness, which measured deviation from geometric simplicity, corresponding to increasing schematism. Additionally, Curvature Histograms along figure contours distinguished the smooth, continuous outlines of naturalistic art from the angular, segmented lines typical of schematic figures.

The resulting feature vectors represented quantitative signatures for each engraving. These data served as input for two complementary machine-learning analyses.

First, K-Means Clustering—an unsupervised learning method—tested whether the data naturally segregated into distinct formal groups without relying on prior stylistic labels. This approach allowed for the identification of potential clusters corresponding to the hypothesized naturalistic and schematic categories purely from measurable morphology.

Second, a Support Vector Machine (SVM) classifier—a supervised learning model—was trained on a subset of figures pre-labeled as “naturalistic” or “schematic” according to existing archaeological interpretations (Mărgărint et al., 2023). The model’s Accuracy and F1-Score on an unseen test set served as objective measures of how effectively it could recognize and generalize the stylistic distinctions.

#### Results and Discussion

The AI-based framework provided a robust and replicable means of evaluating the proposed formal evolution within the Tagus Valley corpus.

The K-Means Clustering analysis revealed clear groupings within the morphological feature space that corresponded to the archaeologically defined stylistic categories. The resulting clusters reflected two principal formal modes: complex, naturalistic figures and simplified, schematic ones. This objective segregation demonstrated that measurable geometric and curvature attributes aligned with traditional qualitative assessments, confirming that stylistic differentiation could be captured through quantifiable features.

Furthermore, visualization of the clustering outcomes indicated the existence of transitional cases between the two poles, suggesting a gradual rather than abrupt stylistic progression. This continuum aligns with the hypothesis that formal evolution occurred through incremental abstraction rather than sudden change, marking a shift from representational fidelity toward symbolic stylization.

The SVM classifier achieved high predictive performance, accurately distinguishing the two groups and demonstrating strong generalization on unseen data. These results confirmed that the extracted feature vectors effectively encoded stylistic information intrinsic to the figures. The classifier’s ability to

reproduce archaeological categorizations through purely quantitative parameters validated the robustness of the formal distinctions.

Overall, both the clustering and classification results provided solid, data-driven evidence for the hypothesized stylistic trajectory from naturalism to schematism. This outcome represents a major advance in rock-art analysis, introducing objective, reproducible methodologies into a field traditionally reliant on qualitative interpretation.

Importantly, the resulting feature-vector signatures now form a transferable toolset for the classification of fragmentary or ambiguous engravings. These quantitative descriptors can also support comparative analyses across different rock-art assemblages, offering a standardized metric for evaluating stylistic convergence or divergence across space and time.

#### Conclusion and Impact

By applying AI, Computer Vision, and Machine Learning to the study of Tagus Valley rock art, this research provided the first quantitative verification of the proposed evolution from naturalistic to schematic representation. Unsupervised clustering confirmed that the visual data naturally formed distinct stylistic groups, while supervised classification quantitatively validated the archaeological hypothesis.

The methodology established here provides a reproducible, scalable, and transferable framework for the quantitative analysis of rock art. Beyond confirming the specific case of the Tagus Valley, it opens new avenues for integrating computational methods into archaeological interpretation worldwide.

This study demonstrates that AI-driven analysis can complement traditional stylistic and typological methods by adding objectivity and reproducibility to cultural-heritage research. It marks a significant step toward a new form of quantitative archaeological science—one capable of transforming qualitative observations into measurable, data-supported insights about human artistic and cognitive evolution.

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## 382. A Grid-Based AI System for Chromatic Reconstruction of the Feo Chapel Frescoes

*Alessia Remondini (Sapienza University of Rome)*

*Paola Pisano (University of Turin)*

#### Introduction

This abstract illustrates how art history, restoration, and AI can converge in the digital and chromatic reconstruction of frescoes that were lost a long time ago. In this specific case, the tool was custom-built for the Feo Chapel in Forlì (Italy), which was destroyed during a bombing in 1944. The frescoes of the chapel were painted jointly by Melozzo da Forlì and his student Marco Palmezzano between 1493 and 1494. The only surviving photographic evidence consists of a series of images taken by the Alinari Brothers, preserved in the archives of Florence from 1938. For project purposes, an initial attempt was made to recolor the photographs using some of the most widely adopted AI-based automatic colorization systems, such as deoldify and Palette.fm. However, these tools proved inadequate, as they failed to correctly



interpret the design and structure of the artwork, applying color in an inconsistent and diffuse way, thus rendering the test ineffective. Melozzo da Forlì's frescoes are characterized by a broad, coherent use of color that gives forms volume. This type of chromatic treatment is not compatible with the training sets and datasets used for the development of current AI-based photo colorization tools.

## Methods and Materials

The input data included:

1. Archival black-and-white photographs of the frescoes in the Feo Chapel;
2. Chromatic references from works by Melozzo da Forlì and Marco Palmezzano, as well as from other contemporary painters, to infer the original color palette;
3. AI-generated chromatic maps, created through interaction with LLMs used as semantic and art-historical reasoning tools to define point-based chromatic hypotheses. The large scale of LLM training increases the likelihood of historically plausible chromatic inference compared to smaller, task-specific models.

These three categories respectively provided the tonal structure (historical photographs), the stylistic context (reference paintings), and the chromatic hypothesis (AI-generated synthesis). The initial tests conducted with deoldify produced visually incoherent results. Even after a fine-tuning attempt, the model consistently applied a yellowish filter reminiscent of the sepia tones typical of photographs from the late 19th and early 20th centuries. This issue is inherent to such models, as the bias originates from the training data: they were trained on photographs depicting people or landscapes - common subjects of that era - thus compromising the results. The frescoes' color tones, on the contrary, are much more intense, structured, and stylistically defined. To overcome these limitations, a new deterministic algorithm was developed in Matlab and later translated into Python.

Inspired by the Deep Photo Style Transfer method, the model uses a grid-based chromatic mapping instead of a stochastic color distribution.

Essentially, a color grid derived from Generative AI is superimposed on the black-and-white image. In this way, the algorithm respects the luminous and geometric subdivision of the reference image. The main operational phases are:

1. Color Extraction – generation of a chromatic map through k-means clustering to identify dominant tones;
2. Grid Overlay – spatial projection of the color map onto the structural sectors of the fresco using adaptive masks;
3. Definition Optimization – application of Laplacian filtering and luminance normalization to preserve details and natural appearance.

A key innovation is the use of a double-mask system, which integrates automatic computation with manual segmentation. This ensures that chromatic areas correspond to coherent architectural or figurative zones, preventing visual artifacts. The translation into Python allowed for more efficient processing, integration with opencv, and a modular approach. The system generates eight different colorized versions of each fresco by varying the intensity and blending between drawing and color layers, offering multiple interpretative hypotheses.

## Results

The tool showed a clear improvement in terms of chromatic fidelity and structural coherence of the output. There was a 35% reduction in chromatic deviation and a 20% increase in the SSIM index compared to the reference model deoldify. Visually, the frescoes recolored with this tool recover the tonal and chromatic balance typical of Melozzo da Forlì: blues and golds appear luminous, while reds and pinks are softer. The lighting effect recalls the perspective and rational illumination of Piero della Francesca, restoring volumetric depth and spatial coherence. The stress test confirmed the robustness of the system: even in complex scenes with multiple figures and decorations, the color distribution remains consistent. The grid overlay operates coherently, and the interaction between the two input layers produces precise and harmonious results.

## Discussion

This project demonstrates that computational recolorization can serve a dual purpose: as a tool for digital restoration and as a method of art-historical analysis. By transforming visual reconstruction into a reproducible process, it redefines the way lost or heavily damaged artworks can be studied.

The software thus becomes a diagnostic instrument, capable of revealing hidden compositional structures and the chromatic logic of Renaissance masters. Every digital intervention involves a degree of interpretation. However, the grid-based method ensures traceability and transparency, as every mapping parameter is documented and verifiable. This confers scientific rigor to the process, distinguishing it from subjective or decorative approaches to digital colorization. This approach, extendable to other destroyed or faded fresco cycles, offers a non-invasive and scientifically reproducible solution for the preservation and digital enhancement of cultural heritage.

Ultimately, the research asserts that digital reconstruction does not aim to replace the original, but rather to reactivate its chromatic logic, constructing a visual hypothesis born from the collaboration between humanistic expertise and artificial intelligence.

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## 386. Linking Ground and Aerial Perspectives: A Vision-Based Workflow for Archaeological Surface Survey

*Kyriakos Sgouropoulos (Democritus University of Thrace)*

*Apostolos Sarris (University of Cyprus)*

*Dushka Urem-Kotsou (Democritus University of Thrace)*

Recent advances in remote sensing and computer vision are transforming the way archaeologists document and interpret landscapes. This study presents a workflow that integrates field-based documentation with vision-based image analysis to detect and interpret surface evidence. The workflow comprises: (a) digital recording of surface finds by fieldwalkers using GPS-enabled mobile devices, (b) automatic detection of finds in drone imagery using a machine learning algorithm (Faster R-CNN) for object detection, and (c) magnetometric prospection used to map subsurface features.

The method was developed and tested in the MapFarm archaeological project, where real-time recording of surface finds produced detailed density maps. These maps were compared with automatic detections from aerial imagery using a heatmap-based Structural Similarity Index (SSIM), which offered a spatial measure of how closely the two datasets matched and how surface visibility affected detection accuracy. By integrating these results with geophysical data, it is possible to produce multi-layered maps that relate surface artifact densities to buried architectural features. Together, these experiments demonstrate how deep learning and remote sensing can complement traditional field observation, offering new insights in the spatial organization of archaeological sites.

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Mandorlo, A. (2024). *Discovering and Recording Archaeological Features during a Survey Using an Unmanned Aerial Vehicle and QField: Application and Integration for Studying the Countryside Surrounding Perugia, Umbria (Italy)*. *Proceedings*, 96(1), 2. <https://doi.org/10.3390/proceedings2024096002>

#### 447. Safeguarding Azulejo Heritage: A Deep Learning Approach to Pathology Detection and Monitoring

*Liane Lin (National Laboratory for Civil Engineering)*

*Mariana Santos (National Laboratory for Civil Engineering)*

*Sara Pires (National Laboratory for Civil Engineering)*

*António Antunes (National Laboratory for Civil Engineering)*

*Gonçalo Jesus (National Laboratory for Civil Engineering)*

*Dora Roque (National Laboratory for Civil Engineering)*

*Marluci Menezes (National Laboratory for Civil Engineering)*

*Lurdes Esteves (National Tile Museum)*

*Anabela Oliveira (National Laboratory for Civil Engineering)*

*José Machado (National Laboratory for Civil Engineering)*

*Sílvia Pereira (National Laboratory for Civil Engineering)*

Portuguese azulejos, or tiles, are traditional glazed ceramic artworks that form an important part of Portugal's cultural heritage. Their preservation highly benefits from proper documentation and careful monitoring of its

conservation condition. However, conventional methods based on visual inspection and manual annotation of superficial damage are highly time-consuming, dependent on the operator's expertise, and often impractical in large-scale or long-term scenarios. Recent studies have begun leveraging machine learning (ML) and deep learning (DL) techniques to automate pathologies detection in historic glazed tiles (Karimi, Mishra, and Lourenço 2024). Most of these approaches focus primarily on identifying pathology areas through bounding boxes (Chaiyasarn and Buatik 2021; Karimi, Mishra, and Lourenço 2024), with limited exploration of segmentation methods. Through a more precise delineation of damaged areas, the segmentation methods allow a mapping and quantification of the extent of deterioration, generating valuable information for supporting robust conservation strategies.

The AI4Az – Artificial Intelligence for Tile Heritage Safeguard project aims to advance the state of research in this field by developing data science methodologies for the automatic extraction of tile damage information from normal RGB and augmented hyperspectral imagery (HIS) through the application of artificial intelligence (AI) tools. Within this context, a Geographic Information System (GIS)-based platform, named TileWatch, is being implemented to support the acquisition, organization, and analysis of data concerning the conservation state of ceramic tiles. This platform will integrate information from multiple sources, including expert conservation assessments, heritage management reports, and contributions from the general public, with the purpose of facilitating collaboration and long-term documentation and monitoring of Portuguese tile heritage.

The present study, conducted within the framework of the AI4Az project, focuses on improving the automatic detection of tile damage to support annotation processes and to extend current methodologies toward pixel-level segmentation. The proposed approach employs the You Only Look Once (YOLO) algorithm for damage detection and evaluates a set of segmentation architectures, including YOLO-seg, Mask R-CNN, SAM 2, and OMG-seg, with the objective of identifying the most appropriate model for integration into the TileWatch platform.

Three complementary datasets were used in this study. The first is an existing labeled dataset previously published and made available by earlier research (Karimi, Mishra, and Lourenço 2024). The second is an anonymized archival dataset composed mainly of mobile phone images acquired in field surveys and institutional or personal archives. The third consists of high-resolution RGB photographs captured with professional cameras under more controlled conditions. Together, these datasets provide images of varying quality and resolution, encompassing the five most frequently observed damage types in Portuguese tiles: glaze detachment, restorations, bio-colonization, fractures, and missing elements. This diversity contributes to a more comprehensive representation of real-world conditions and supports the development of models with greater generalization capability.

Following the acquisition of the high-resolution photographs, the initial phase of the work consisted of manually annotating damaged areas to generate the required labels for training. Both open-source and proprietary software tools were employed to annotate the images using bounding boxes corresponding to each identified damage type. The main challenge encountered during this stage was the large size of the high-resolution photographs, which considerably increased annotation time and computational effort. This limitation further demonstrated the importance of developing automated methods capable of assisting and accelerating the labeling process.

Building on the work of Karimi et al. (Karimi, Mishra, and Lourenço 2024), the latest version of the YOLO algorithm (v12) was trained and tested for tile damage detection using the combined datasets. Computational experiments were performed using the DEUCALION supercomputer, a national high-performance computing infrastructure managed by the Portuguese Foundation for Science and Technology (FCT). This system provided the necessary computational capacity for training and evaluating the deep learning models used in this study. Different experimental configurations were explored, varying hyperparameters, image resolution settings, and the proportion of data allocated to training, validation, and testing. The use of high-resolution images posed specific difficulties, as YOLO requires input images to be resized to fixed dimensions. To address this issue, the Slicing Aided Hyper Inference

(SAHI) method was employed. This approach divides large images and their corresponding annotations into smaller, overlapping sections, thereby generating a richer and more balanced training dataset. Furthermore, SAHI allows the algorithm to process large images during inference without requiring manual segmentation, preserving spatial information and improving detection performance.

At the current stage of the project, the archival and high-resolution images are being subjected to data augmentation procedures to increase the variability of the training dataset and enhance the robustness of the model. The applied transformations include rotation, color and illumination adjustments, cropping, and other operations that simulate the heterogeneity typically found in real-world acquisition conditions. The objective of this process is to improve the capacity of the trained model to detect damage across different lighting conditions, tile styles, and camera types.

Once the detection model achieves satisfactory performance, the outcomes of this research will have two principal implications. First, images collected through the GIS-based TileWatch platform will be automatically analyzed to detect and classify visible damage, facilitating the evaluation and monitoring of conservation states and assisting heritage professionals in prioritizing interventions. Second, the identified regions of interest will serve as preliminary annotations for segmentation models, expediting the generation of pixel-level labels required for the next phase of the project. The application of segmentation techniques will allow a more precise delineation of damaged areas, supporting the quantification of deterioration and the extraction of more relevant indicators for tile conservation monitoring.

Ultimately, the integration of these AI-based methods within the GIS based TileWatch platform is expected to contribute to the establishment of an efficient digital workflow for the documentation, monitoring, and management of tile heritage. By combining automated detection and segmentation algorithms with expert knowledge and collaborative data collection, the AI4Az project seeks to promote a more systematic, efficient, collaborative and data-driven approach to cultural heritage preservation.

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### RT35: Chronological Modelling III: a Round Table on Time in Computational Archaeology

Thomas Huet, CNRS  
Eythan Levy, University of Zurich

**Location:** Hörsaal 05  
**Session Format:** Round Table

This round table aims at discussing the current challenges and future perspectives on the modelling of time in archaeology. Duration: 2h30.

Some 30 years ago, the introduction of GIS into the archaeological toolbox sparked a ‘spatial turn’ in the discipline, greatly improving the interoperability of spatial data. However, no such integrated tool exists for managing temporal data. Chronological methods are highly diverse (e.g., seriation, stratigraphy, cross-dating, absolute dating), each typically handled by different software applications and libraries. The lack of interoperability between software outputs, formats and standards hinders the ability to understand cultural developments across different societies. In our view, the time has come to make chronological data more interoperable through the use of standardised formats (e.g., EDTF), relative temporal relationships (e.g., before/after), and specialised software (e.g., OxCal). Such an approach could pave the way for a Temporal Information System (TIS), enabling the calculation of a

temporal metric for the rate of human cultural evolution (see our position paper: Huet & Levy, 2025).

We invite all interested colleagues to participate in the open-forum discussion at the round table.

**Position paper:**  
Huet, T., & Levy, E. (2025). Foreword – Archaeometry special issue on chronological modelling. *Archaeometry*, 67(S1), 1-6.  
<https://doi.org/10.1111/arcm.13095>

|               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|---------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 14:00 – 14:10 | <b>Foreword</b><br><i>Thomas Huet and Eythan Levy</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| 14:10 – 14:40 | <b>Topic 1: Epistemology of archaeological time</b><br><i>chair: Joan Anton Barcelo</i><br><br>History and Archaeology, sciences of societies in time, are based on the ordering and clustering of events, but differ mainly on the different nature of the proxies they use. History uses mainly authored time-stamped writings (e.g., diplomatic letters, political writings) while Archaeology uses anonymous time-uncertain material culture (e.g., ceramic and stratigraphic sequences). How can such archaeological series be grouped to create periods? To what extent can two periods be considered as contemporaneous? |
| 14:40 – 15:10 | <b>Topic 2: Archaeological time in practice: cross dating, anchor dates, cultural periods</b><br><i>chair: Keith May, James Taylor</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |

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Archaeologists often deal with multi-aligned chronological data: a piece of material culture can be related to a stratigraphic unit containing other objects, to site-wide stratigraphy with groupings and phasing, to broader landscape and/or cultural periodisation, to seriation, to artifact types found in other archaeological cultures, and to so-called 'absolute' dates from scientific dating methods (e.g., radiocarbon dates). How, in practice, are these data aligned with each other? How is uncertainty propagated over different chronological assessments?

**15:10 –  
15:25**

Break

**15:25 –  
15:55**

**Topic 3: Formats, standards and interoperability**

*chair: Florian Thierry*

Deterministic dates, whether seemingly exact (e.g., 79 AD), approximate with uncertainties (e.g., 80/81 AD), or relative (e.g., after 68 AD), can be encoded unambiguously using standards such as ISO 8601, EDTF, or OWL-Time. Such date expressions can serve as the basis for space-time gazetteers (e.g., PeriodO and ChronOntology) and be reused in ontologies (e.g., CIDOC CRM). However, these formats, gazetteers and ontologies cannot directly express probabilistic temporal distributions, such as those derived from radiometric dating. Furthermore, the different ad hoc chronological formats and syntaxes used by chronological software (e.g., OxCal, ChronoModel, or ChronoLog) add a further layer of complexity. How can we foster interoperability between all these formats and standards?

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**15:55 –  
16:25**

**Topic 4: Mathematics, Algorithms and Software**

*chair: Joe Roe*

A host of mathematical methods and algorithms exist for both deterministic and probabilistic temporal assessments in archaeology. Software packages (libraries), as well as interactive software applications, are being used to solve a wide variety of chronological problems, such as seriation, Bayesian calibration of radiocarbon dates, or chronological network modelling. Mastering the whole array of available chronological methods, algorithms and tools can be challenging. Is a unified, standardised approach feasible and desirable? And if so, what concrete steps can be taken to achieve it?

**16:25 –  
16:30**

**Conclusion: Towards a Temporal Information System?**

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## RT41: New Advances and Directions of 3D Analysis in Archaeology

*Corey Noxon*, Ritsumeikan University

*Markos Katsianis*, University of Patras

*Wilhelm Kerle-Malcharek*, University of Konstanz

*Jannis Werner*, University of Cologne

### **Session Format:** Round Table

The field of 3D analysis has made significant advances since the formation of the 3D Spatial Analysis SIG at CAA Tübingen in 2019 (e.g. Hostettler et al. 2024). A founding aim of the SIG was to define the meaning of 3D Spatial Analysis, with early efforts focusing on larger scale GIS-based approaches to better incorporate three-dimensional data into modern archaeological practice. Since that time, the possibilities for digitizing objects—particularly cultural heritage objects—have reached levels of quality, ease of use, and availability that make it possible for anyone with a smartphone to engage in the process, and now forms part of the standard toolkit for many practitioners. Significant improvements in 3D capture technology and accessibility since the founding of the SIG has prompted the need for a re-evaluation of 3D technologies, analytical approaches to the ever-increasing corpus of 3D data, and ways in which we can better incorporate these advances into analytic and synthetic knowledge-building workflows.

Reflecting these changes, the 3D Spatial Analysis SIG is updating its name to the 3D Analysis SIG and is looking to update its aims and goals to better reflect the current technological and analytical landscape. As part of this

process of update and renewal, this roundtable session will have participants discuss the state of the field, identify the gains we've made, the areas where we need to improve, and where we aim to go moving forward. Discussion will initially be focused on the following topics: definition of 3D analysis in archaeology, practical applications of 3D analysis in archaeology, project management, "best practices" for data management, 3D outputs directed towards other researchers and the public at large, and new directions for the SIG in general.

Recorded 3D data has become a more mainstream method to display artifacts and other archaeological data, but data reuse for analytical purposes still has a lot of room to grow. Participants will discuss improvements in archaeological applications of 3D data as well as new and upcoming analytical approaches. While GIS applications remain as relevant as ever (e.g. Dell'Unto & Landeschi 2022), the increased accessibility of 3D digitization makes object-based analytical approaches like GMM more accessible as well. In addition to these approaches, recent work related to room illumination and similar visual-based approaches are just a small sampling of the ever-increasing analytical approaches that are opening up to archaeologists and serve as starting points for further discussions.

As photogrammetry and other forms of 3D digitization become more commonplace for recording sites, features, and artifacts both in the field as well as part of subsequent post excavation processing, how can we better integrate this "new" form of data within the broader assemblage of recorded archaeological data? How can the digitization of archaeological findings be positioned as an integral part of the archaeological process and archaeological project management? Are we at a stage in which certain aspects of digitization techniques, such as 3D scanning, can replace prior recording methods, or should multiple methods be continued in tandem? Are there ways in which 3D digitization can be better streamlined to smoothly integrate into existing workflows, whether it be on-site recording or lab-based documentation? What are ways in which we can better integrate 3D scan data into other

forms of gathered data to help provide a more holistic and contextualized record of archaeological sites or features?

An equally important part of project management is data management. As data is gathered it must be organized and stored. While less glamorous than other aspects of 3D work in archaeology, the manner in which data is organized and stored becomes increasingly more important as the amount of gathered 3D data increases. Multiple discussions have been had stressing the importance to data management practices like FAIR and CARE, but broadly accepted implementations of these ideals are still far from standardized. Taking a broader view, long-term archival storage of 3D data is another pressing topic of serious importance to the field. Existing database structures are rarely suited for the large file sizes involved in 3D, whether it be large high resolution models, or the hundreds or thousands of images used to create photogrammetry-based scans. If the totality of the gathered and processed data is too large to store long-term, are there any particular types of data that we all agree should be stored as a minimum? What file types and formats should data be stored in? Are some lossy formats “good enough”, and if so, how lossy can they be? If archiving 3D models is difficult, how difficult is it to archive the results of 3D analysis? A shared understanding of the realities of these data management challenges could help to provide some realistic guidelines for practitioners moving forward.

Finally, 3D recordings of archaeological sites, features, and artifacts are significantly multi-functional in nature. The same 3D models that are processed for analytical purposes can also be processed for broader public consumption. One of the most approachable methods for this is preparing an individual artifact or component for public access on a 3D model viewer, but uncertainty related to commercial platforms calls into question the long-term sustainability of this approach and stresses the importance of alternative platforms and modes of model presentation. The contexts of objects play a key role in our understanding of objects, and while there has been some work in the field, developing and implementing ways in which individual 3D objects

can be better visualized within broader contexts for public consumption and incorporated into a larger site narrative seems another area to be further explored. Incorporating AR and VR technologies is another way in which we can possibly provide new ways to create immersive environments to help provide better spatial understandings of cultural heritage sites. While advances have been made along these lines as well, there still seem to be significant barriers in their implementation. Rather than focusing on individualized approaches to these issues, are there ways in which a shared platform can be developed to further improve accessibility in this form of data presentation?

The problems and opportunities facing 3D analysis in archaeology evolve and change as the field moves forward, and are too numerous for any individual to tackle on their own. This roundtable will hopefully provide a chance to pool the experience, background knowledge, and additional resources of the participants to help identify, discuss, and continue to engage in these areas of movement in the field. With the renewal of the 3D Analysis SIG we hope to be able to continue these discussions and work in a more closely connected and collaborative manner in an attempt to move beyond a patchwork of isolated solutions and help drive the field forward together.

## S42: The Reuse of Digital Archaeological Archives and Data: Pathway to New Knowledge or Dead End?

Christophe Tuffery, Ministère de la Culture et UMR 8068 TEMPS

Sebastien Plutniak, CNRS

Loup Bernard, Université de Strasbourg / CNRS

Marie Stahl, École Française d'Athènes

Stéphanie Delaguet, IRAA, UAR 3155, CNRS, Aix Marseille University

**Location:** Hörsaal 03

**Session Format:** Standard

The amount of archaeological data published or archived in digital formats is increasing. In the context of the open science movement, disciplinary repositories (e.g. ADS, tDAR, OpenContext), journals (e.g. the *J. of Open Archaeological Data*), and specialized archive services contribute to this trend.

The FAIR principles are enthusiastically claimed as a guide in this way, and tireless efforts are made to make digital data findable and accessible – sometimes interoperable – and reusable. But, are FAIR-compliant “reusable” data actually reused? In recent years, data reuse has become a concern, as reflected by conference sessions [1], publications [2, 3], standards [4], and collective projects [5]. Indeed, it raises controversial and sensitive matters:

- The scientific “publish or perish” rationale and archiving rationale “preserve or perish” can prove antagonistic. To what extent have studies based on data reuse actually demonstrated significant benefits in knowledge or methods to ground the idea that digital data conservation is worth it?
- The funding and support of open-science initiatives is made on the promise of their usefulness through reuse. This goes against the fact that professional norms in archaeology today still firmly promote the

production of *new* data. What if data openly published is not reused? How to define and track reuse?

- When digital data is reused, how is it done? The reuse of openly published data can conflict with requirements in data sovereignty. How and to which extent are the CARE principles considered when it comes to digital archaeological data?

This session is intended to address these problems and other related issues. We welcome presentations about design studies grounded on data reuse, applied methods, results obtained, difficulties encountered and how they have been overcome, as well as data reuse policies, digital infrastructures, and monitoring.

Presentations should reflect a diversity of projects and actors, particularly those who are not members of academic and research communities (indigenous voices and practitioners) and who come from a variety of regions, especially those that are often underrepresented.

Presentations should also illustrate good practices, some of which could be used to define guidelines for encouraging and ensuring proper reuse of archaeological archives.

### References:

1. EAA 2024. Session “Old Excavations and Finds, New Data and Interpretations: The Use of Archives in Current Archaeological Research Projects”. DOI: <https://doi.org/10.58079/vovk>
2. Gupta, N. et al. 2023. “The CARE principles and the reuse, sharing, and curation of indigenous data in Canadian archaeology.” *Advances in Archaeological Practice* 11 (1): 76-89. DOI: <https://doi.org/10.1017/aap.2022.33>
3. Tuffery C. 2023. “Contribution to the recent history of archaeology by using some digital humanities methods and techniques applied to field recording documents of an archaeological site excavated in 1970s” *Journal of Data Mining & Digital Humanities*, DOI: <https://doi.org/10.46298/jdmdh.10847>

4. Marwick, B & S. E. Pilaar Birch. 2018. "A standard for the scholarly citation of archaeological data as an incentive to data sharing" *Advances in Archaeological Practice* 6(2): 125-143.

DOI: <https://doi.org/10.1017/aap.2018.3>

5. Project TETRARCHs Telling Stories with Archaeological Data.

<https://www.tetrarchs.org>

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**14:00 – 14:20** 34. A political perspective on the power of data reuse  
*Rita Gautschy (DaSCH, University of Basel)*

**14:20 – 14:40** 100. AI and the CIDOC-CRM: the first steps of STAIHRE  
*Muriel Van Ruymbeke (Université du Luxembourg)*

**14:40 – 15:00** 179. Designing ArchaeoVault: a National Repository for Non-Field Archaeological Data Through Cross-Disciplinary Focus Groups  
*Filip Hájek (Independent researcher); Michal Lorenz\*; Illyria Brejchová\*; Jan Adler\*; Hana Kubelková\*; Peter Tkáč (Czech Academy of Sciences)*

\* Masaryk University

**15:00 – 15:20** 190. Defeating the digital Dark Ages? Constructing and maintaining a Roman settlement database of the Netherlands  
*Alexandre Peix\*; Philip Verhagen\*; Mark R. Groenhuijzen\**

\* Vrije Universiteit Amsterdam

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**15:20 – 15:40** 374. Reusing digital archaeological data within AIR: multiple pathways for multiple goals  
*Paola Derudas (Lund University); Federico Nurra (French National Institute of Art History)*

**15:40 – 16:00** 402. From archives to anchors: reusing 1910 documentation to re-map Pathyris  
*Aneta Skalec (Institute of Mediterranean and Oriental Cultures PAS); Wojciech Ejsmond (Institute of Mediterranean and Oriental Cultures PAS); Julia Chyla (Faculty of Archaeology, University of Warsaw); Jakub Stępnik (Faculty of Archaeology, University of Warsaw)*

**16:00 – 16:30** Discussion

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## 34. A political perspective on the power of data reuse

*Rita Gautschy (DaSCH, University of Basel)*

The author is responsible for a research data infrastructure wherein archaeological data currently makes up a non-negligible percentage of all data. The daily work includes regular communication and exchange with various national and international stakeholders. Funding agencies request that data is archived in a FAIR repository and as open as possible at the end of a research project for at least 10 years to allow for reproducibility of results and the reuse of data. This is a reasonable demand, considering that researchers are funded by public money. But over time the amount of data will increase considerably. The demand of storing and archiving data contrasts with initiatives concerned with keeping our ecological footprint to a minimum (Benardou & Baillot 2025). Quite apart from that, the requirement that data must be FAIR

contradicts the fact that persistent identifiers will no longer be resolvable or lead to a kind of tombstone page if the data is deleted. It is high time to consider how, in the foreseeable future, decisions will be made about which data should be kept directly accessible in the long term (hot storage), which should be made available on request with a slight delay (cold storage), and which can be deleted after a minimum storage duration of e.g. 10 years. So far, however, I encounter little understanding and willingness from funders to invest any thoughts on the following non-trivial questions: Who decides about what will be stored or deleted? What criteria are applied to take such a decision? The approach of funding agencies to these issues is simplistic: it is all about numbers and simple solutions. And therein lies the great danger for archaeological data, but more broadly, for humanities data in general. While it may be true that data in certain fields become obsolete after 10 years, this does not apply for some archaeological and other humanities data. A photo documentation of an excavation, for example, does not lose its value – this refers to data that is irretrievably lost if deleted. Other such examples are 3D models of monuments or digital scholarly editions which sometimes take decades to be created. Thus, a decision based on a certain amount of years is clearly a bad criterion for humanities data. A second idea is to base decisions on download, use and reuse numbers – this is a much better track if applied within disciplines and if made transparent what the numbers measure. One very popular key performance indicator (KPI) requested by funders is the number of registered users. If, however, data is accessible openly this number means nothing. The number of downloads of a dataset also gives only a first indication – if data is available as linked open data with persistent identifiers and directly accessible, there is no need to download the data. Currently, I encounter little reuse of data, one of the reasons being that there is not a significant amount of clean data available in a form which would foster reuse. As long as we do not adhere to the use of a set of controlled vocabularies and more standardised data models it will remain a very time-consuming task to include external data in our own datasets. At my own institution the desired presentation of the data sometimes conflicts with the preparation of the data with maximum reuse potential. The

latter relates to the topic of the session: pathway to new knowledge or dead end? It is understandable that we want to present our data in a form tailored to what our research project was focused on – limitations or restrictions in the form of standard data models or controlled vocabularies thus may seem like a dead end. On the other hand, if we want to ensure that our archaeological data will remain accessible in the long-term, we must prove that it is used and reused.

## References

Benardou, A. & Baillot, A. 2025. “DARIAH goes Green: Internal Environmental Guidelines”. Accessed September 27, 2025. [https://www.dariah.eu/wp-content/uploads/2025/09/DARIAH-Goes-Green-Internal-Environmental-Guidelines\\_01.pdf](https://www.dariah.eu/wp-content/uploads/2025/09/DARIAH-Goes-Green-Internal-Environmental-Guidelines_01.pdf).

## 100. AI and the CIDOC-CRM: the first steps of STAIHRE

*Muriel Van Ruymbeke (Université du Luxembourg)*

The STAIHRE (Semantic Tools and Artificial Intelligence for Historical Research Enhancement) project aims to extract, interlink and therefore, reuse, historical knowledge available in processed data produced by researchers at C2DH (Center for Contemporary and Digital History – University of Luxembourg). The project has been made possible through the collaboration of several researchers from the C2DH Digital Research Infrastructure. The project began with the design of a prototype system tested with data collected and created for the digital exhibition about the Second World War in Luxembourg (ww2.lu). This paper presents the ongoing efforts to transform this data corpus into a structured and interoperable knowledge graph and ontology that together form a foundation for semantic historiography. It focuses on the computational modeling of historical narratives through explicit and machine-readable semantics.

Material, methods and results:

The second world war in Luxembourg data corpus consists of over one hundred and fifty files. These contain sixty-three multilingual notes, thirty-three videos' transcripts, two hundreds and eighty-six archival metadata, one hundred and three bibliographic references, and around eighty geospatial data documenting Luxembourg's wartime and occupation experience between 1940 and 1945.

At this stage, we processed through the pipeline five of the sixty three multilingual notes JSON files, including document-level metadata. It represents approximately five percent of the case study corpus. First, each file has been parsed to extract free text and structured fields (i.e. identification of keys and corresponding values ). Subsequently, the files were analyzed using a multilingual large language model (OpenAI GPT-4.1) configured to conform to a strict JSON schema for entity and relation extraction. This step was involved through Natural Language Processing tasks (Named Entity Recognition and Entity Relation Extraction).

Our data pipeline first identifies named entities including persons, organizations, places, events, documents, and concepts. Then the model extracts types of relations such as MEMBER\_OF, OCCURRED\_AT, HEADED\_BY, PLACED\_UNDER, and FOUNDED, while normalizing temporal expressions to ISO-standard dates and time spans. Provenance is maintained through document-level enrichment, including titles, descriptions, coordinates, and bibliographic references. Relations are reified as assertion nodes that contain subject–predicate–object triples and link to associated TimeSpan, Place, and Document entities.

In addition to this knowledge graph, an OWL (Web Ontology Language) ontology defines the conceptual vocabulary that governs the extraction and modeling process. The generated ontology, based on the first five percent of the data, comprises fourteen classes, thirty-two object properties, and

twenty datatype properties, organized using domain and range constraints as well as subclass hierarchies.

In line with recent work combining AI and ontological models from the CIDOC CRM family to enrich historical and heritage research ( see for example Felicetti and Niccolucci 2025; Felicetti, Himmiche, and Somenzi 2025) the proposed ontology provides a transparent and interoperable schema designed for alignment with the CIDOC CRM conceptual reference model. It also addresses the specific representational requirements of historical corpora, including temporal uncertainty, multilingual contexts, and provenance tracking.

The current knowledge graph, based on five percent of the total corpus of data from the WW2.lu digital exhibition, consists of 8,892 RDF (Resource Description Framework) triples, individual statements of the form subject–predicate–object representing single facts. It includes 1,576 unique subjects (distinct entities such as people, organizations, or documents), 45 predicates (relations that connect entities, e.g., memberOf, occurredAt, hasDate), and 2,615 objects (targets of those relationships, which can be other entities or literal values such as names or dates). We have identified 1,576 typed instances (rdf:type), that is, entities explicitly assigned to a class such as Person, Organization, or Event. The graph exhibits an average node degree of 5.2 (each node participates in about five relationships on average), a median degree of 2 (half of the nodes have two or fewer connections), and a maximum degree of 342 (the most connected entity participates in 342 relationships).

Discussion:

We look forward to expanding our field of investigations to all other files included in the data corpus of our case study. We are eager to enrich the generated OWL ontology and knowledge graph. Nevertheless, we expect that the size of the latter will complicate its visualization and manipulation



somewhat. Furthermore, we will need to handle other types of extraction sources (e.g. from data organized in spreadsheets). We will also have to work on tracking down redundancies and ambiguities. Finally, we will need to refine the OWL ontology in order to subsequently facilitate seamless alignment with the classes and properties of the CIDOC CRM. Then, the next steps will be to expand the data analyzed to other corpus related with the second world war in Luxembourg.

#### Conclusions:

Preliminary results from this integrated framework suggest that even partial processing (again, approximately five percent of the available data) can reveal coherent temporal and institutional structures within the corpus. The ontology and knowledge graph prototype jointly demonstrate how semantic historiography can bridge archival description and computational analysis, enabling historians to interrogate, visualize, and interlink complex wartime data through transparent and explainable semantic models. This framework establishes a reusable semantic infrastructure for historical data modeling by uniting multilingual text processing, ontology-driven knowledge representation, and interactive visualization.

#### References:

- Felicetti, Achille, Aida Himmiche, and Miriana Somenzi. 2025. "Knowledge Graphs and Artificial Intelligence for the Implementation of Cognitive Heritage Digital Twins." *Applied Sciences* 15 (18): 10061. <https://doi.org/10.3390/app151810061>.
- Felicetti, Achille, and Franco Niccolucci. 2025. "Artificial Intelligence and Ontologies for the Management of Heritage Digital Twins Data." *Data* 10 (1): 1. <https://doi.org/10.3390/data10010001>.

## 179. Designing ArchaeoVault: a National Repository for Non-Field Archaeological Data Through Cross-Disciplinary Focus Groups

*Filip Hájek (Independent researcher)*

*Michal Lorenz (Masaryk University)*

*Illyria Brejchová (Masaryk University)*

*Jan Adler (Masaryk University)*

*Hana Kubelková (Masaryk University)*

*Peter Tkáč (Czech Academy of Sciences)*

#### Background

Contemporary archaeology produces large, heterogenous digital datasets that often remain dispersed across teams and local storage without unified curation, interoperable description, long-term preservation planning or availability for reuse by others. ArchaeoVault is a national initiative to address this gap for non-field archaeological data. The repository's mission is to provide a central, sustainable, and standardized infrastructure for storing, describing, sharing and preserving such data originating in the Czech Republic as well as relevant international projects.

Preliminary community mapping revealed substantial variability in data types, formats, and metadata depth across research groups. To translate this heterogeneity into actionable repository policy and design, we established discipline-spanning focus groups tasked with co-defining minimum standards and best practices aligned with FAIR, while remaining realistic for day-to-day research workflows.

#### Main objectives

- 1) Identify a suitable data model for a repository system for archaeological data.

- 2) Describe archaeologists' data practices with a focus on the role of epistemic artifacts (data) in knowledge production.
- 3) Characterize the nature and types of data in use: data types, file formats, granularity and degree of structure.
- 4) Identify the epistemological assumptions of the domain.
- 5) Describe user practices and requirements.
- 6) Identify organizational and institutional constraints.

#### Research questions

- 1) How must an archaeological repository be structured to enable effective management of data and knowledge?
- 2) How do archaeologists use data to produce new knowledge?

#### Methodology/Focus Groups Design

There will be a series of moderated 90-minute focus groups with invited experts from universities, museums, laboratories and independent teams from across the Czech Republic. ArchaeoVault organizes heterogeneous archaeological data into five data categories: geospatial data, 3D data, laboratory analysis data, anthropological data and databases including complex and synthetic data. Each session is thus organized around one of these data categories and uses a common scenario to ensure comparability across groups. Sessions combine open discussion with a Nominal Group Technique (NGT) segment to surface, cluster, and prioritize requirements. Outputs across groups using thematic coding of transcripts and artifacts from the NGT steps will be synthesized. Cross-category comparison will identify common denominators (baseline standards) and domain-specific divergences (category extensions).

#### Contribution to the Field

The study offers a practice-anchored path from heterogeneous, real-world datasets to workable, FAIR-aligned standards that researchers can actually meet. Rather than importing generic schemas, ArchaeoVault's approach co-designs standards with domain experts, balancing methodological nuance

with interoperability and preservation demands. By presenting the focus-groups method, instruments, and comparative synthesis, we provide a reusable template for other heritage communities facing similar heterogeneity.

## 190. Defeating the digital Dark Ages? Constructing and maintaining a Roman settlement database of the Netherlands

*Alexandre Peix (Vrije Universiteit Amsterdam)*

*Philip Verhagen (Vrije Universiteit Amsterdam)*

*Mark R. Groenhuijzen (Vrije Universiteit Amsterdam)*

Over the past twelve years, we have created a database of Roman settlements in the Netherlands to support our research on settlement patterns in the Roman frontier zone (the limes). This database was designed for a maximum of three internal users and built in MS Access. The input data was largely taken from the Dutch national archaeological database ARCHIS (<https://archis.cultureelerfgoed.nl/>) and reworked to collate information from different findspots that were related to Roman settlement locations. This framework was then extended with information from databases of individual researchers (for example, military gear, brooches, and coins) and excavation reports, which are mostly stored digitally in what is currently called DANS Dataverse (<https://dataverse.nl/dataverse/dans>). The resulting data have proved useful to better understand the development of settlement patterns (Verhagen 2023), transport networks (Groenhuijzen 2018), and agricultural production (Joyce 2019) in the study region. However, it was never destined to be shared or reused by researchers outside our group.

In recent years, we have opened new collaborations and a new project, extending both the spatial scope and the contents of the database. This development not only increased the quantity and complexity of the data but also

the difficulty of maintaining database integrity and accessibility. At the same time, other researchers have also created new data sources, in particular the Portable Antiquities of the Netherlands database (PAN; <https://portable-antiquities.nl/pan/#/public>), and the national database ARCHIS has undergone updates and revisions of its structure and interface. Also, questions of copyright have arisen. It became clear that there are no guarantees for long-term sustainability or interoperability, even within organizations that are responsible for national data structures. For academic data, the situation is even worse, with datasets either being completely inaccessible, listed in written reports, or only available by personal request to each researcher. This is, it seems, quite typical of archaeological data management these days, despite efforts to promote Open Science practices.

Our plan to solve, at least partly, this issue was to reassess our database from its foundations, aiming for a more future-proof design.

First, the MS Access relational database was ported to PostgreSQL. In this process, we had to very carefully synchronize the stored data with the latest version of the available data stored in the public repositories. PostgreSQL is licensed under the permissive PostgreSQL License, which is free of cost and vendor lock-in. It avoids ongoing licensing fees that jeopardize long-term sustainability. PostgreSQL is very flexible, but it needs customization for a more user-friendly experience and demands the creation of dedicated interfaces for internal use (create, read, update operations) and a different one for external use (query, read, and visualize operations).

Secondly, we needed to define a system of authorization. While all data has been made freely available for research purposes, we cannot share everything online because of copyright restrictions. In particular, the location of individual archaeological finds is not meant to be openly shared. This restriction leads us to the necessity of aggregate data. For example, a spatial

analysis of specific find types can be presented by applying spatial aggregates, such as hexagons or squares, that do not reveal individual find locations. However, from the perspective of Open Science, the underlying information should also be accessible and verifiable. These seemingly opposite requirements compelled us to create different levels of detail that may be shared with different user groups.

Thirdly, we had to consider easier ways to explore the data than is currently possible, using the existing relational database. To achieve this, we plan to implement a virtual knowledge graph system that enables the exploration of a wider array of relationships within the data. It will offer it in a different virtual layer, preserving the original data structure and avoiding duplication that could lead to synchronization issues. This approach will provide visual and semantic representations, making it easier to navigate and interpret the dataset. The layer demanded the construction of an ontology that can be connected to existing international frameworks, such as TIR-FOR (<https://tir-for.iec.cat>) or ArkeoGIS (<https://arkeogis.org/en/>) and CIDOC CRM (<https://www.cidoc-crm.org/>). The database sources, like ARCHIS and PAN, already utilize the Dutch Archeologische Basisregister vocabulary (<https://linkeddata.cultureelerfgoed.nl/thesauri/archeologischbasisregister>). Through virtualization, the system will also make explicit how these existing classifications can interact with each other. The resulting graph layer can further serve as a foundation for custom visualizations, such as interactive dashboards designed for wider public engagement.

The selection of reliable and tested tools was crucial to fulfill the specific functionalities required by our database. We aim to make the data interoperable, reusable, and extendable in the long run. However, we have no guarantee that we will be able to keep our data in the air in ten years' time, or that dedicated visualizations will still work. It therefore remains to be seen if we can truly defeat the digital Dark Ages in this project.

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## 374. Reusing digital archaeological data within AIR: multiple pathways for multiple goals

Paola Derudas (Lund University)

Federico Nurra (French National Institute of Art History)

### Context

Various definitions have been proposed for the reuse of archaeological data. A central distinction concerns reuse by humans, aimed at achieving cognitive interoperability, and reuse by machines, which supports technical interoperability. More recently, a third form of interoperability has emerged that transcends traditional documentary standards such as the CIDOC-CRM. This new form of interoperability is enabled through Large Language Models (LLMs) and opens up new possibilities for reasoning across heterogeneous datasets.

Regarding human-centred reuse, Jeremy Huggett has proposed a definition that emphasises remixing, which is the creative reconfiguration of existing and newly generated data by both the original creators and subsequent

users (Huggett, 2018). From a technical standpoint, the FAIR principles define reuse as the technical and semantic readiness of data for use by others, ideally across disciplines and systems. This approach prioritises metadata richness, licensing clarity, provenance documentation, and adherence to shared standards, thereby ensuring that data remains FAIR beyond the scope of the original project.

However, archaeological data are inherently heterogeneous, a characteristic that continues to challenge interoperability and slow down data sharing across projects and repositories. While large-scale initiatives such as the AR-IADNE Project have sought to address these issues through top-down approaches to data normalisation and standardisation, our work adopts an opposite, bottom-up perspective. Our focus is on defining an information system and digital infrastructure tailored to the archaeologists' needs, structuring information from the outset according to principles that promote accessibility, interoperability, and reusability, even if imperfectly.

Within this framework, AIR (Archaeological Interactive Report, <https://air.ht.lu.se/>) serves as a web-based platform embedding a 3D visualisation environment. It functions as an online archive for documenting, managing, and publishing archaeological investigations and their heterogeneous datasets, including spatial data, metadata, images, videos, and 3D models (Derudas et al., 2023). AIR has been developed with the archaeologist's workflow at its core, while maintaining alignment with descriptive models and controlled vocabularies to ensure data reusability throughout the entire information lifecycle, from data collection to publication.

At the structural level, we identified the core entities and relationships that describe archaeological practice and cross-referenced them through properties aligned, where possible, with the CIDOC-CRM. This provides a robust and interoperable infrastructural scaffolding, while the exposure of data through APIs in machine-readable JSON format ensures machine interoperability. Beyond these technical aspects, we have placed strong emphasis on interface design to make complex datasets more accessible to users. This is achieved through minimalist layouts, pictograms, dynamic indices, 3D canvases for exploration, and web-mapping components for GIS data.

## Main Argument

Now that the AIR system has reached a mature stage and is actively used to manage 10 excavation projects, we have begun exploring its potential for data reuse through a series of targeted experiments.

The first experiment focused on human-centred reuse. It involved retrieving and extracting analytical and spatial information from multiple projects in order to integrate and repurpose these datasets in a GIS environment. This process demonstrated how data generated in distinct archaeological contexts can be remixed and combined to produce new interpretative outcomes.

The second experiment addressed machine-centred reuse. Here, we tested the use of Large Language Models (LLMs) via the AIR API to co-construct excavation reports based on available project documentation. This experiment aimed to assess how LLMs could facilitate the synthesis and interpretation of complex, heterogeneous data.

A third, ongoing experiment extends these principles to the analysis and extraction of information from osteological and pathological datasets.

Taken together, these experiments suggest that a renewed conceptual and technical framework is now required for the reuse of archaeological data. This framework must be capable of supporting multiple pathways of reuse: by human users, by machines, and by LLMs.

The LLM experiment demonstrated the potential for automated report drafting but also revealed the importance of structured metadata for contextual accuracy.

Our findings suggest that digital infrastructures for archaeology must operate on two complementary levels:

Human reuse, promoting cognitive interoperability through clear interfaces, flexible querying, and visualisation tools;

Machine reuse, ensuring technical interoperability through FAIR-compliant data exposure, REST APIs, and LLM integration.

We argue that tools for archaeological data reuse must be designed to mediate between archaeologists, computational systems, and emerging AI

technologies. This would enable archaeologists and all potential data users to access, interpret, and build upon the digital archaeological record in distinct yet interconnected ways.

## Applications and Implications

Our experiments on the reuse of archaeological data highlight the necessity of designing digital infrastructures that address both human and machine requirements. On the one hand, such systems must ensure that archaeologists and other stakeholders can retrieve, select, and download data for a wide range of research and professional purposes. On the other hand, as datasets grow in scale and complexity, these infrastructures must also support collaborative modes of interaction between humans and machines, enabling the co-construction of information and knowledge.

This co-construction introduces and implies a new form of archaeological work that requires the inclusion of machine expertise and computational capacities in human reasoning processes. Establishing such practices involves developing workflows that remain transparent, methodologically sound, and aligned with established research standards, while still allowing for the interpretative flexibility that defines archaeological reasoning.

Looking ahead, the most significant challenge may lie in defining reliable ways to train machines to “understand” archaeological needs, i.e. to process data in a manner consistent with the discipline’s epistemological frameworks and research objectives. This will require teaching models to understand and interpret data not only through patterns and metadata but also through contextual and conceptual lenses grounded in archaeological practice, bridging the gap between data-driven processing and the conceptual frameworks through which archaeologists interpret the material record.

Ultimately, the implications extend beyond the mere reuse of digital data. They point towards a future in which archaeologists collaborate with machines, each party contributing complementary strengths to the process of knowledge creation. In this sense, the reuse of archaeological data becomes not only a technical issue, but also an epistemological one, reshaping how

we define, construct, and share archaeological understanding in the digital age.

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## 402. From archives to anchors: reusing 1910 documentation to re-map Pathyris

Aneta Skalec (*Institute of Mediterranean and Oriental Cultures PAS*)

Wojciech Ejsmond (*Institute of Mediterranean and Oriental Cultures PAS*)

Julia Chyla (*Faculty of Archaeology, University of Warsaw*)

Jakub Stępnik (*Faculty of Archaeology, University of Warsaw*)

Pathyris, a Ptolemaic times town in southern Egypt, also known under its earlier name as Per-Hathor, preserves a dense palimpsest of textual, architectural, and landscape evidence. Much of what is known survives in dispersed archival documentation—notably the Italian expedition's 1910 photographs, plans, and a field Notebook with sketches. Ongoing landscape

transformation complicates direct comparison with the past. This paper asks whether reusing those early twentieth-century records can produce new, testable spatial knowledge fast enough to inform current research and protection.

## Methods and materials

Archival corpus & inspection. We assembled the 1910 materials (Notebook with sketches, plans, and archival photo set) and described for each item: provenance, content, and likely vantage.

1. Field survey (ground observation only). A systematic survey compared the present-day terrain with the archival imagery. Using topographic clues and built elements visible today, we:
  - o located camera stations for selected archival photographs,
  - o confirmed major landscape changes over the last century, and
  - o traced the enclosure wall line of the temple complex in today's at the site/in the current terrain.
2. Establishing fixed reference points. The matched viewpoints and persistent features were formalised as reference anchors to georeference the town plan preserved in the Notebook. This step connects the archival sketch plan to the modern topography with explicit control points.
3. Linking rock-cut structures. We identified rock-cut features on the hill slope that correspond to constructions documented in the Notebook. These had been difficult to place previously because their spatial relationships were unclear; matching on the ground resolves those relationships.
4. Surface traces and base layers. All visible surface traces (including rock-cut lines, terrace edges, and quarry marks) were digitised as lines and draped over high-resolution satellite imagery and a digital surface model (photogrammetric DSM) available to the team.
5. 3D reconstruction. Combining high resolution DSM, photogrammetry models and observations from the field works, allows us to spatially reconcile the Notebook and its sketches of the architecture remains with the current terrain. This opens the possibility toward staged 3D reconstruction of the urban landscape.



## Results

1) Enclosure wall extent and plan anchoring. The correlation of archival photographs with present-day terrain provided enough fixed anchors to georeference the Notebook plan within the site's topography. This stabilises the plan spatially and enables coherent comparison across sources.

2) Camera-station map & structure identification. Recovered camera positions allow one-to-one identification of features depicted in 1910 imagery with structures still visible today. This resolves ambiguities in earlier readings of the photographs.

3) Rock-cut features and terrace logic. Field observation and line-mapping reveal a terraced organisation of the urban surface. Lines visible in the town area continue further south-east as quarry traces. This modifies the 3D reconstruction of the sketches of the excavations from the 1910.

4) 3D models. Combining all of the above information with the results of photogrammetry and high-resolution DSM allows us to prepare a 3D reconstruction of the buildings and streets of Pathyris.

## Discussion

Pathway to new knowledge, not a dead end. Reusing the 1910 documentation, when paired with careful ground observation, produced new spatial anchors and a coherent town-plan placement that did not exist in any single source. The field documentation, including mobile GIS and photogrammetry, is opening the way for full 3D spatial reinterpretation of the town's urban landscape itself.

What made reuse succeed here? Three practical factors were decisive:

- Anchors first. Treat archival images as potential control points by re-finding camera stations and persistent features.
- Link the sketch to terrain. Use those anchors to georeference the Notebook plan, then check against present traces.

- Map the obvious. Digitise every visible rock-cut line and terrace edge; simple linework over good base layers can unlock relationships that desk interpretation would miss.

## Conclusions

In the case of Per-Hathor/Pathyris, archival reuse—focused on photographs, a Notebook with sketches, and a historic plan—has moved us beyond citation into spatially anchored knowledge: a placed town plan, identified camera stations, a refined temple-enclosure line, a plausible temple foundation-deposit findspot, and a terraced hypothesis that structures the next steps, allowing full reconstruction of the Pathyris urban landscape. The approach is lightweight, transparent, and replicable for other Egyptian sites where early documentation and modern terrain can still be brought into register.

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## S51: From Satellite to Unmanned Platforms, the Computation of LIDAR Dataset for Archaeological and Heritage Projects

*Moisés Hernández Cordero, Austrian Archaeological Institute (ÖAI-ÖAW)*

*Irene Petschko, Austrian Archaeological Institute (ÖAI-ÖAW)*

**Location:** Hörsaal 05

**Session Format:** Standard

LIDAR (light detection and ranging) is becoming a survey technique intensively used in archaeological prospections as well as in Building Heritage (Doneus, M. et al., 2020, Fontana, G. 2022, Parcero-Oubiña, C 2022). However, most presentations in archaeological sciences focus on analysing the results obtained by LIDAR rather than explaining why LIDAR was considered more appropriate than other techniques. Usually, papers with a more technical approach are dedicated to illustrating how historical features were detected (Orengo, H.A., Petrie, C.A, 2018, Stott, D. et al., 2015, Kokalj, Ž., Mast, J. 2021) or how the filtering of vegetation (Doneus et al., 2020, Brede et al., 2022) was accomplished. Some others gather instances of the use of LIDAR in archaeology but without analysing quality or reasons for selecting this technique vs others (Stott, D. et al., 2015, Vinci et al., C, 2024). Only few are dedicated to standardizing procedures when processing or presenting results for archaeological projects (Kokalj, Ž. 2025). Recently, with the introduction of machine learning for data analysis, new approaches to query the data are being published with greater focus on the postprocessing phase (Trier et al., 2019, Verschoof-van der Vaart et al., 2020, Berganzo-Besga, I. et al., 2021, Doneus et al., 2022).

This session would like to explore different applications of the LIDAR, shifting the focus from the overall research results to the previous technical phase within a project. The idea is to discuss/debate the use of LIDAR for heritage projects based on:

- what platform do they use (Satellite, plane or UAV) and why (resolution, cost, accessibility flexibility),
- how this might affect the final product (point cloud, raster) and the research questions of the project,
- new processing methodologies (filtering vegetation, noise removal, feature detection, software comparison/alternatives, ...), and
- encountered problems in the data acquisition and the post processing phase (filtering vegetation, identifying features...).

We invite researchers interested in computation workflows, comparison of surveying techniques, cost-effect, quality of recorded data and setbacks during processing to present in this session. We welcome talks dealing not only with successes in the application of LIDAR but also with difficulties and failures that occur when delivering data and results, “the process of learning a craft often involves making mistakes along the way” (Gómez Coutouly et al. 2021). Overall, through this session we wish to focus in the exchange of experiences and discussion of senior/experienced scientist and technicians as well as junior researchers regarding the use of LIDAR for their projects. We believe that this topic might open new avenues and approaches to guide projects interested in applying this technique in the future.

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**12:00 – 12:20** 346. Hierarchical Point Patch Transformer for Semantic Segmentation of High Resolution Multimodal Archaeological LiDAR Point Clouds

*Nicola Lercari\**; *Alma Ament\**; *Qingyan Lu\**; *Maocheng Xiong\**; *Evan Eames\**; *Mina Yacoub\**; *Yiming Du\**; *Davide Tanasi (University of South Florida)*; *Rosa Lanteri (Parco Archeologico e Paesagg. di Siracusa, Eloro, Villa del Tellaro e Akrai)*; *Rodolfo Brancato (University of Naples Federico II)*; *Saverio Scerra (Soprintendenza per i Beni Culturali e Ambientali di Ragusa)*

\* LMU Munich

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| <b>12:20 – 12:40</b> | 368. Evaluation of the Usability of the Czech National LiDAR in an Archaeological Research of Cultural Landscapes of the 20th Century<br><i>Barbora Weisssova (Czech Academy of Sciences); Kryštof Seleši (Czech Academy of Sciences)</i>                                       |
| <b>12:40 – 13:00</b> | 415. The end of LiDAR? Revealing archaeological sites under the Amazon dense forest canopy without LiDAR<br><i>Iban Berganzo Besga (Barcelona Supercomputing Center); Jonas Gregorio de Souza (Pompeu Fabra University); Hector A. Orengo (Barcelona Supercomputing Center)</i> |

### 346. Hierarchical Point Patch Transformer for Semantic Segmentation of High Resolution Multimodal Archaeological LiDAR Point Clouds

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*Rodolfo Brancato (University of Naples Federico II)*

*Saverio Scerra (Soprintendenza per i Beni Culturali e Ambientali di Ragusa)*

Light Detection and Ranging (LiDAR) is an active remote sensing technique that builds a three-dimensional map, or point cloud, of an environment. Early archaeological LiDAR applications used large sensors mounted on manned aircraft to survey vast, forested regions of Mesoamerica, Northern and Central Europe, and Southeast Asia, revealing previously unknown structures and settlements. Current drone-based LiDAR systems can record up to 32 returns per pulse, penetrating dense vegetation and producing high-resolution point clouds. Such detail is crucial in Mediterranean environments where layered vegetation obscures archaeological features affected by centuries of human activity. Using drone-based LiDAR at Heloros and Kamarina in coastal Sicily, we achieved over 400 points/m<sup>2</sup> (5 cm spacing), enabling detection of archaeological features covered by dense Mediterranean shrubs. However, performing high-resolution semantic segmentation on these high spatial resolution LiDAR datasets to automatically remove vegetation and detect archaeological features remains challenging and requires customized methods with strong spatial reasoning. For example, off-the-shelf classifiers (e.g., RIEGL's "Off-Terrain" filter, LAsTools lasclassify, and FUSION/LDV) produced inconsistent results, as these tools frequently misclassify dense vegetation and archaeological remains, thus hindering an effective class-based filtering and subsequent archaeological inference. In addition, drone-based LiDAR surveys produce billions of observations, making manual annotation slow, error-prone, and costly. The imbalance between abundant unlabeled and scarce labeled data motivated us to develop a point cloud classifier based on a self-supervised approach. In this paper, we present our drone-based LiDAR pipeline from the field to a deep learning-based automated data classification framework. The latter is based on a hierarchical point patch embedding approach using a transformer-based tokenizer trained on large amounts of unlabeled data with a masked reconstruction proxy task, and a transformer-based U-Net finetuned on small amounts of labeled data to perform downstream semantic segmentation on tokenized archaeological LiDAR point clouds. Our preliminary results indicate that our

hierarchical transformer-based framework has the potential to offer a practical, accurate, and scalable pipeline for high-resolution semantic segmentation that leads to automated vegetation removal and archaeological feature detection in drone-based LiDAR. Beyond immediate applications at the Greek sites of Heloros and Kamarina in Sicily, our approach establishes a methodological foundation for developing more generalizable and powerful tools for archaeological LiDAR that can support archaeological reconnaissance and landscape interpretation in densely vegetated or otherwise complex settings.

### 368. Evaluation of the Usability of the Czech National LiDAR in an Archaeological Research of Cultural Landscapes of the 20th Century

*Barbora Weisssova (Czech Academy of Sciences)*

*Kryštof Seleši (Czech Academy of Sciences)*

#### Introduction

The present work examines the usability of the Czech Republic's national LiDAR dataset (DMR 5G), offered as open data by the ČÚZK (the Czech Office for Surveying, Mapping and Cadastre), for research on the cultural landscapes of the 20th century. The study is part of the interdisciplinary research project OP JAK The Land Gone Wild: Archaeological and Transdisciplinary Research of Resilience Strategies in the 20th Century, which explores both visible and invisible traces of the violent Nazi and Communist totalitarian regimes left on the Czech landscape.

The LiDAR dataset (DMR 5G) was produced by the Czech Office for Surveying, Mapping and Cadastre in cooperation with the Ministry of Defence and the Ministry of Agriculture between 2010 and 2013. The data were acquired by airborne laser scanning using a RIEGL LMS-Q680 sensor mounted on an L-410 aircraft, flying at an average altitude of 1,200–1,400 m.

The resulting point cloud was filtered and generalized through automated and manual classification, followed by “robust filtration” and interpolation to a  $1 \times 1$  m grid (or  $5 \times 5$  m in agricultural land). Terrain points were smoothed using the Atlas DMT algorithm, allowing a maximum vertical adjustment of 0.16 m. The model declares a mean vertical accuracy of  $\pm 0.18$  m in open terrain and  $\pm 0.3$  m under vegetation (ČÚZK 2021). The available products include the DTM (.tiff) and preclassified point cloud (.las), featuring a single category (ground), as well as a point cloud that underwent robust filtering and standard classification (based on ASPRS 2019), which is currently available only upon special request.

#### Methods and Materials

Using two sample sites and a range of visualization and analytical tools, this paper compares the visibility of known features in products derived from the Czech National LiDAR, point clouds created using an UAV, and data captured with a tablet equipped with a LiDAR sensor. In addition, we included results from traditional Structure from Motion (SfM) photogrammetry to clearly demonstrate the advantages and limitations of LiDAR.

The evaluation focuses primarily on data quality and cost-effectiveness, including the required manpower, computational power, and time consumption involved in creating and/or analyzing the products.

The micro-regional case studies examine the potential to detect features at two sites: the Klecany airfield near Prague, where aircraft revetments are preserved, and a newly discovered and well-preserved anti-aircraft (FlaK) position in Bohnice, Prague. Both sites were developed in the spring of 1945 as part of Prague's air defense infrastructure during World War II.

#### Results

The results of our work demonstrate the potential, advantages, limitations, and possible dead ends in the use of the Czech National LiDAR for archaeological research.

The standard Czech LiDAR products, while highly accurate for cartographic and engineering purposes, are not always sufficient for archaeological

interpretation of medium-sized features such as aircraft revetments or other terrain remains (e.g., fortifications). For conflict archaeology, as well as archaeological studies in general, greater vertical precision and gentler filtering parameters are prerequisites for better visibility of relevant anthropogenic forms.

#### Discussion

A large-scale remote sensing approach, usually the first step in non-destructive landscape examination, can be misleading when applied to the LiDAR dataset offered by the ČÚZK and should be considered only one of several methods in landscape investigation. For sufficient documentation of known sites, we recommend using a UAV, a tablet with a LiDAR sensor, or simple SfM photogrammetry—depending on the size, vegetation cover, and specific needs of each project.

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### 415. The end of LiDAR? Revealing archaeological sites under the Amazon dense forest canopy without LiDAR

*Iban Berganzo Besga (Barcelona Supercomputing Center)*

*Jonas Gregorio de Souza (Pompeu Fabra University)*

*Hector A. Orengo (Barcelona Supercomputing Center)*

LiDAR technology has revolutionised remote sensing in archaeology by enabling highly accurate three-dimensional mapping of terrain and vegetation. Numerous studies have applied aerial LiDAR to capture detailed terrain and

structural information across a wide range of environments (Berganzo-Besga et al., 2022). In archaeology, one of the most interesting regions to analyse using LiDAR has been the Amazon (Prümers et al., 2022), where dense forest cover presented significant challenges for traditional optical remote sensing.

Tropical forests have long concealed the true scale and diversity of pre-Columbian Amazonian societies. However, despite all these advances driven by new archaeological paradigms and technical developments, we only know a very small fraction of the extension of past Amazonian occupation where deforestation has expanded or LiDAR dataset are available (usually in marginal areas of the rainforest). Given the high cost of LiDAR surveys, which explain their restrictive distribution, and the extension of the Amazonian forest, our information about the location of settlements in the area remains limited. From a Heritage protection perspective, unknown sites cannot be protected and those in areas of potential deforestation are in danger. Therefore, with the aim of identifying them on a large-scale, this research seeks to demonstrate the possibility of detecting archaeological sites in dense forested areas of the Amazon without using lidar.

Analysis of several known sites (de Souza et al., 2018), in both deforested and forested areas, has revealed that anthropogenic sites leave a spectral signature in satellite imagery that differs from that of their surroundings. This research was carried out using various indices, such as Enhanced Vegetation Index and Normalised Difference Red-Edge, derived from satellite imagery sources, including Landsat-5 and Sentinel-2. By eliminating the need for costly LiDAR, our open-source workflow unlocks global, rapid, and reproducible archaeological survey of rainforest archaeology.

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## S52: Beyond Fun and Games? Rethinking Archaeogaming, Play, and Digital Heritage

*Aris Politopoulos, Leiden University*

*Sebastian Hageneuer, Berlin-Brandenburg Academy of Sciences and Humanities*

**Location:** Hörsaal BIG

**Session Format:** Standard

What happens when archaeology meets play? Archaeogaming has grown from a niche into a lively field, exploring how games and playful media intersect with archaeological research, heritage practices, and public engagement. Building on last year's discussions, this session continues to open the field — but shifts the focus more explicitly to questions of accessibility, inclusivity, and the critical limits of play.

We invite contributions that explore how playful tools — from video and board games to VR installations, museum interactives, and game engines — shape archaeological knowledge, communication, and teaching. Play and games clearly provide opportunities for experimentation, collaboration, and joy. Yet we also ask: what happens when play is not universally fun? How do these media exclude or marginalize particular audiences? How do they unintentionally reinforce narratives, power structures, or cultural stereotypes?

Accessibility is central here: games and playful experiences can widen participation in archaeology, but they can also create new barriers. Physical disabilities, technological requirements, and linguistic or cultural differences can all shape who gets to play — and who remains excluded. Similarly, inclusivity demands attention to representation and diversity: whose pasts are being told through games, whose bodies and voices are included or omitted, and

how can archaeogaming be a platform for decolonial and feminist perspectives (Gray 2020; Nakamura 2009; Politopoulos/Mol 2023)?

The “limits of play” also invite critical scrutiny. While play has often been seen as inherently liberating, recent scholarship highlights that games can also capture and constrain, reinforcing dominant ideologies or even reproducing systems of surveillance capitalism and extractive economies. In archaeology, too, playful tools can unintentionally “gamify” heritage in ways that flatten complexity, privilege entertainment over reflection, or exclude traditional forms of non-western play.

At the same time, archaeogaming is uniquely placed to experiment with alternative forms of being. Game engines and playful design can be harnessed for critical storytelling, participatory heritage projects, and collaborative learning environments (Graham 2020; Reinhard 2018, 2024). New technologies such as generative AI, immersive XR, and interactive platforms open up further possibilities — but also demand new ethical considerations.

By highlighting both opportunities and risks, this session aims to provide a more balanced perspective on playful archaeology: one that recognizes its capacity for experimentation and joy, while remaining attentive to its exclusions, blind spots, and unintended consequences. We particularly welcome contributions that cross disciplinary boundaries, engage with community-based practices, or present creative and experimental approaches.

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|---------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 11:00 – 11:20 | 51. Playful inclusion? Contemporary art and archaeological 'technoheritage'<br><i>Monika Stobiecka (University of Warsaw)</i>                                                                               |
| 11:20 – 11:40 | 164. Project CLAY: Integrating Ancient Craft and Cutting-Edge Technology to Engage with Archaeology<br><i>Kristin Donner (Laguna College of Art + Design); Laura Harrison (University of South Florida)</i> |
| 11:40 – 12:00 | 201. From Tomb Raider to Time Machine: Ethics, Ownership and the Limits of Play in Heritage-Based Games<br><i>Elisabeth Monamy (Archeomuse)</i>                                                             |
| 12:00 – 12:20 | 214. DigUp! – Excavating Archaeological Practice Through Play<br><i>Lana Elizabeth Allan*; Paraskevi Gavra*; Maria Sotomayor Chicote*</i>                                                                   |

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*\*University of Cologne*

**12:20 – 12:40** 235. The Archaeology Worldbuilding Game  
*Colleen Morgan (GB); Aris Politopoulos (Leiden University); Kathryn Killackey (Independent); Stuart Eve (Wessex Archaeology)*

**12:40 – 13:00** 259. A virtual journey to the past: serious games as tool for public engagement with prehistoric heritage  
*Xavier Roda Gilabert\*; Susana Vega Bolívar\*; Jorge Martínez-Moreno\*; Rafael Mora Torcal\**

*\* Universitat Autònoma de Barcelona*

**13:00 – 14:00** Lunch break

**14:00 – 14:20** 303. Dust, Desire, and Discovery: Women, Archaeology, and their Representation in Games  
*Dajana Ehlers (University of Cologne)*

**14:20 – 14:40** 306. How do we want to play with the past? Authoritarian and democratic archaeology in contemporary gaming  
*Ian Regueiro Salcedo (University of Ferrara)*

**14:40 – 15:00** 340. Pixels, Perspectives, and the Past – Diversity in historical game settings  
*Charlotte Tornos (University of Cologne)*

**15:00 – 15:20** 391. The Poetics of Reconstruction: An Interpretative and Atmospheric Framework in Virtual Heritage and its Contribution to Archaeogaming—The Case of Wukang Mansion LBVR Exhibition in Shanghai

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*Jiahao Yan (Shanghai Jiao Tong University); Huaqing Huang (Shanghai Jiao Tong University)*

**15:20 – 15:40** 448. Echoes from Earth: Exploring Archaeology Through Play  
*Lava Mohamad (University of Cologne)*

**15:40 – 16:00** Discussion

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## 51. Playful inclusion? Contemporary art and archaeological 'technoheritage'

*Monika Stobiecka (University of Warsaw)*

In 2016, artists Nora Al-Badri and Jan Nikolai Nelles secretly scanned the famous bust of Nefertiti in Berlin's Neues Museum and released the resulting 3D data online as „The Other Nefertiti". This act, which the artists described as “digital piracy,” (Elias 2019) invited people worldwide to download, remix, and reimagine the Egyptian queen. Their gesture, illegal yet deeply political, transformed one of the most recognizable symbols of Western archaeological collections and museums into a site of open, collective, and playful engagement. The 3D model was later printed, exhibited for the first time in Egypt, and even buried there as a speculative archaeological artefact for future discovery. In subsequent years, the dataset was reanimated in „Nefertiti's Bot” (2018), an AI-driven installation that enabled the bust to “speak back” to its colonial and digital afterlives. Together, these works demonstrate how artistic practices can use digital tools to question the ownership, visibility, and accessibility of archaeological heritage.

In my presentation, I discuss how Al-Badri and Nelles mobilize playfulness as a critical and participatory mode of engaging with the archaeological past. Their projects reject both the logic of museum spectatorship and the efficiency-driven ethos of digital reproduction. Instead, they turn heritage into a performative, affective field of experimentation. The act of sharing a 3D model becomes a form of playful inclusion - an invitation to reappropriate, reinterpret, and reanimate heritage that has been physically and symbolically locked away in Western collections (Hana 2023). Yet this play is not innocent. As Al-Badri herself notes, “technoheritage” - her term for the hybrid, digitally mediated heritage objects emerging from such acts - exists within unequal conditions of access and power. The possibility of “playing with” Nefertiti depends on who owns the devices, possesses the skills, and participates in digital culture. Thus, while the project democratizes access, it simultaneously reveals the limits of digital openness.

The concept of play is central to this reflection. While play has often been associated with pleasure and experimentation, recent scholarship has emphasized its ambivalence. It can both liberate and constrain, include and exclude. In „The Other Nefertiti”, play functions as a double-edged tool: it opens access to heritage through collective creativity, yet it also exposes how access remains mediated by digital infrastructure and data policies. Users are encouraged to engage with Nefertiti’s image - to remix, copy, and share - but this engagement takes place within global museums systems of data control and copyright. The artists’ act of “piracy” thus becomes a subversive form of digital play that unsettles both museological authority and techno-utopian narratives of openness (open data, open access).

“Nefertiti’s Bot”, produced two years later, further expands this experiment. Using machine learning and natural language processing, the artists animated the bust, giving it an autonomous voice capable of interacting with visitors. Speaking from within the digital realm, the Bot comments on colonial history and the politics of representation. In this way, Al-Badri and Nelles translate the notion of play into a critical dialogue between human and non-human agents.

These projects challenge the assumption that digital heritage necessarily promotes neutrality, transparency, or universality (Dallas 2015). On the contrary, they reveal how digital reconstructions can reproduce colonial hierarchies by privileging Western institutions as the primary custodians of cultural data. „The Other Nefertiti” reverses this logic. By releasing the model into the public domain, the artists relocate the authority of interpretation from the museum to a dispersed, networked community of users. The resulting multiplicity of remixes, reprints, and reinterpretations forms a participatory archive that resists closure. This is where the “playfulness” of the project acquires its full meaning: it becomes an emancipatory strategy for reclaiming the right to interact with, and imagine anew, the material traces of the past. Ultimately, I argue that Al-Badri and Nelles’s works expand our understanding of what playful interaction with heritage can mean. Their projects move beyond the institutional boundaries of the museum and the logic of digital spectacle to propose a more reflexive, affective, and ethical engagement with the past. Through their notion of “technoheritage,” they demonstrate how art can translate complex questions of restitution, ownership, and participation into experiential, interactive forms. Play, in this context, is not a distraction from heritage but a way of thinking with it - a mode of acting within and against the structures that have long defined what counts as knowledge, property, and authenticity.

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## 164. Project CLAY: Integrating Ancient Craft and Cutting-Edge Technology to Engage with Archaeology

*Kristin Donner (Laguna College of Art + Design)*

*Laura Harrison (University of South Florida))*

How do we introduce students to cutting-edge technology while facilitating creative, hands-on exploration? Is it possible to engage differently-abled learners and reluctant readers alongside high achievers? How do we encourage archaeological play with curiosity, respect, and reflection? The authors explore these questions through the development and implementation of a pilot program, which conveys archaeology to the classroom in innovative ways. The result is a multimodal pedagogical solution that delivers archaeological education that is accessible, inclusive, and exciting.

Project CLAY: Creative Learning through Archaeology is an educational outreach endeavor, which champions inclusivity by taking a multimodal approach to archaeology and heritage study. Project CLAY lessons satisfy state curriculum requirements - and surpass them - through a week-long, immersive educational experience. Students are transported back in time 4,000 years, from a virtual archaeological site (including an interactive photogrammetry model) to a Bronze Age village in ancient Anatolia (simulated within the classroom). As students learn the significance of the 3D printed artifacts they excavate, the artifacts transform into tools. Students experience Bronze Age life by practicing ancient craft techniques as potters, weavers, and merchants. Their senses are fully engaged through sight, sound, smell, and touch as they explore topics such as regional standardization, individualization, ritual, identity, and trade. The program concludes with a comic storytelling activity, in which students author dynamic "object biographies" and reflect on their experiences through the traditional mediums of pencil and paper.

After field-testing this pilot program in middle school classrooms in California and Florida and responding to critical observations from students and

teachers, we expanded into a week-long summer camp model in 2025. Partnering with our University 3D Lab and Office of Youth Experiences, we invited a fresh cohort of middle school students to engage with archaeology and cutting-edge technology like never before. As they explored our artifact database (via Sketchfab), created 3D scans of artifacts (utilizing a FARO 8-Axis Quantum Design ScanArm), and designed personalized team stamps (for fabrication with a Bambu Lab A1 3D Printer) the students were encouraged to consider current and future applications in the fields of archaeology, heritage, and STEAM. An end-of-camp Gallery Exhibition, hosted by the Lab, showcased student accomplishments, both individual and collaborative, demonstrating their experiential knowledge of traditional craft techniques, engagement with advanced digital technologies, and thoughtful reflection on what they had learned.

Our research found that incorporating digital tools, immersive 3D visualisations, and haptic technologies enriches the educational experience, as the students' senses are engaged in novel ways. As Arnott and colleagues note, 'technologies, when used in a playful way and integrated into early years pedagogies as "tools" rather than distinct and different objects ... provide opportunities for creativity.' (Arnott et al. 2017, 54) Recent advances in digital archaeology, including the development of virtual tours of archaeological sites, 3D models of features and artefacts, and 3D prints enhance multisensory engagement with archaeology, and reinforce the goals of early childhood education and outreach activities.

The historical comics integrated into our lesson plans allow students to envision the past, and begin to grasp the human connection between individuals and societies in the past and present. This creates empathy around human struggles and challenges. Comics increase overall engagement and may serve as accessible texts for emergent readers, reluctant readers, and children with learning differences. (English 2021)

By integrating haptic technologies, both ancient and modern, the inaugural Project CLAY Archaeology + Art Camp empowered students to think critically and creatively. Each day, campers faced new challenges that simulated real-world archaeology. Working in teams, they explored unique excavation scenarios, analyzed complex findings, and applied their skills to interpret ancient lifeways, building confidence in their abilities as budding archaeologists.

As we look forward to summer 2026, we aim to discuss our multimodal approach to archaeology, assess our curriculum and identify shortcomings. Do our lessons achieve an ideal balance between instruction and playful exploration? Does Project CLAY meet the diverse needs of our participants? As we entertain opportunities to license our lesson plans, how can we anticipate and address possible barriers to access (including, but not limited to, knowledgeable instructors, print and craft materials, internet, hardware and software)? By continuing to seek feedback from our peers and the communities we serve, we hope to support the evolution of Project CLAY and archaeological play.

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## 201. From Tomb Raider to Time Machine: Ethics, Ownership and the Limits of Play in Heritage-Based Games

*Elisabeth Monamy (Archeomuse)*

Over the past two decades, the boundaries between archaeology, heritage interpretation, and digital play have become increasingly porous. Video and board games now stand among the most influential cultural media through which the public encounters the past. From Tomb Raider to Assassin's Creed, from 7 Wonders to Mombasa, games not only visualise ancient monuments and lost civilisations but also construct emotional and narrative frameworks that shape how we imagine history. This paper examines what happens when entertainment and heritage intersect — and where they begin to diverge ethically.

While archaeogaming has developed as a field of academic inquiry (Reinhard 2018; Graham 2020; Politopoulos & Mol 2023), public debates around accuracy and representation remain fragmented. Much attention has been given to the educational potential of “serious games” and museum interactives, yet less to the ethos of play — the implicit values, hierarchies, and exclusions embedded within ludic heritage. Drawing on examples from both digital and analogue gaming, this contribution explores how games function as cultural storytellers, and how they can either democratise or distort archaeological knowledge.

The first section investigates the entertainment bias of mainstream heritage-themed games. Here, history often serves as aesthetic backdrop or narrative flavour rather than as critical engagement. Tomb Raider, for instance, turns archaeological discovery into a spectacle of individual heroism, echoing colonial tropes of exploration and extraction. Board games such as Civilization or Puerto Rico gamify historical processes of empire-building and resource exploitation, rewarding players for behaviours that mirror real-world systems of domination. Such designs, though rarely malicious, raise ethical



questions about how much simplification is acceptable in the name of playability — and when abstraction becomes erasure.

The second part focuses on pedagogical and museum-based initiatives that attempt to use play for education and engagement. Institutions like the British Museum, the V&A, and the Smithsonian have incorporated digital games or gamified experiences to broaden access to collections. These projects reveal the double edge of play: while interactive media can transform learning into participation, they also risk reproducing established narratives or excluding audiences without digital literacy, financial means, or physical access. Inclusivity thus becomes not only a matter of design, but of infrastructure and philosophy.

A third thread explores the grey zones where play mediates between authenticity and imagination. Many games operate in this liminal space, where factual accuracy coexists with creative speculation. Historical board games, in particular, often use abstraction to communicate complex systems — trade, warfare, politics — but in doing so, they naturalise certain worldviews. Who becomes the agent of history in these systems? Whose labour, suffering, or creativity remains invisible? Examining game mechanics alongside visual and textual design reveals that representation is never neutral: even the absence of certain groups or voices functions as a statement about whose past is considered playable.

Central to this discussion is the question of ownership. Who owns the stories of ancient Egypt, Mesopotamia, or the Maya? Who has the right to design, narrate, or profit from them? In both the USA and Europe, recent debates in digital heritage and museum studies (Champion 2015; Mol & Ariese 2022; Huvila 2020) highlight growing awareness of cultural authorship and participatory ethics. Indigenous and decolonial game projects — from Māori-led digital storytelling to African-designed historical simulations — illustrate how games can reclaim rather than appropriate heritage. These examples show

that play can become a mode of cultural self-representation when developers, scholars, and communities collaborate on equal footing.

At the same time, the “limits of play” demand critical scrutiny. The ideal of play as inherently liberating — a safe, joyful space for exploration — obscures the ways in which games can reinforce dominant ideologies or replicate extractive logics. As Gray (2020) and Nakamura (2009) argue, play can reproduce systems of exclusion, gender bias, and racialisation. Within heritage contexts, gamification can flatten complexity, turning ritual, trauma, or sacred space into consumable experience. Game engines and virtual environments, though powerful tools for reconstruction, risk turning archaeology itself into spectacle, prioritising visual immersion over epistemic rigour.

This paper therefore proposes a framework for ethical archaeogaming, grounded in three principles:

1. Transparency — acknowledging where reconstruction gives way to imagination;
2. Collaboration — involving descendant and source communities in narrative and design;
3. Multiplicity — embracing ambiguity, contradiction, and diverse perspectives as essential features of historical play.

These principles shift focus from producing perfectly “accurate” games to cultivating reflective ones — games that reveal their own processes and invite players to question what they see. They also align with broader movements in critical heritage studies that seek to decentre Western epistemologies and include non-linear, non-competitive forms of play rooted in different cultural traditions.

The paper concludes by returning to the metaphor in its title: the journey from Tomb Raider to Time Machine. If the former symbolises the extractive impulse — to seize, to own, to master the past — the latter evokes the desire to understand and inhabit it empathetically. Between these poles lies the

challenge and promise of archaeogaming: to transform play from a tool of appropriation into a platform for dialogue.

By examining both digital and board games through the lenses of archaeology, ethics, and accessibility, this contribution argues that play can be more than entertainment. It can be a method of inquiry, a form of public history, and a site of negotiation between memory, imagination, and power. Yet to realise this potential, we must remain attentive to its exclusions and blind spots — to who plays, who is played, and who remains unseen on the board.

Ultimately, when archaeology meets play, the question is not only how accurately the past is represented, but how responsibly it is shared. Games have the power to democratise heritage, but also to commodify it. The task ahead is to cultivate forms of play that illuminate rather than obscure, that open the field rather than close it — an archaeology of play that balances curiosity with care, and creativity with conscience.

## 214. DigUp! – Excavating Archaeological Practice Through Play

*Lana Elizabeth Allan (University of Cologne)*

*Paraskevi Gavra (University of Cologne)*

*Maria Sotomayor Chicote (University of Cologne)*

In the winter semester of 2024, during the Archaeogaming Hackathon sponsored by the Foundation for Innovations in Higher Education, and organized by the DiKopA network, a team of three digital archaeologists developed DigUp!, a video game exploring the process of an archaeological excavation from the perspective of a novice field archaeologist. Created within only three days using the software RPG Maker, and with no extensive programming experience, the game demonstrates the growing accessibility of digital tools for archaeological practice and education.

The motivation behind DigUp! stemmed from the recognition that, while archaeogaming has become a more established field, the representation of archaeologists within games remains narrow and often unrealistic. Iconic figures such as Lara Croft or Indiana Jones may inspire adventure, but they rarely reflect the actual scientific, procedural, and collaborative realities of archaeological work (Reinhard 2018). DigUp! seeks to challenge these depictions by offering a grounded, educational, yet entertaining experience in which players move through the authentic stages of fieldwork—excavation, cleaning, photographing, and digitally recording finds using Reflectance Transformation Imaging (RTI).

The design intentionally balances realism with playfulness: dialogues and narrative interactions are informed by genuine field experiences, while light, surreal elements introduce humor and creativity without distorting the disciplinary process. Through this structure, the game aims to bridge two audiences—the general public, who often encounter archaeology only through popular media, and professional archaeologists, who can recognise the nuances of real fieldwork embedded in the gameplay.

Developing DigUp! also raised a series of critical and theoretical questions central to this session's theme. To what extent can archaeologists without technical training create playable, meaningful, and scientifically accurate games? What constraints—technical, temporal, or conceptual—shape accessibility for both creators and players? How might playful representations of archaeological practice avoid reinforcing stereotypes, hierarchies, or exclusions within the discipline itself?

In addressing these questions, our presentation situates DigUp! within broader debates on accessibility, inclusivity, and the critical limits of play. The project highlights how approachable game-making tools can democratise archaeogame creation, allowing scholars and students to participate in digital heritage production without reliance on specialized developers. At the same time, it underscores the need to remain attentive to barriers—technological requirements, linguistic accessibility, and cultural framing—that may restrict who can play or create such games.

DigUp! therefore operates both as a proof of concept and as a reflective case study in the possibilities and responsibilities of archaeogaming. By presenting archaeological work as a collaborative, procedural, and communicative process rather than a solitary adventure, it contributes to more inclusive and accurate representations of the discipline. We argue that games developed by archaeologists themselves can function as critical tools for public engagement, self-reflexive storytelling, and participatory heritage practice—expanding not only who plays archaeology, but also who has the authority to shape its narratives.

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### 235. The Archaeology Worldbuilding Game

*Colleen Morgan (GB)*

*Aris Politopoulos (Leiden University)*

*Kathryn Killackey (Independent)*

*Stuart Eve (Wessex Archaeology)*

Within fiction and game development creators produce worlds to talk about (theirs or other) culture. What we could describe, in archaeological terms, as the act of integrating history, ecology, geology to bring an imaginary world to life. As demonstrated by Morgan (2025) worldbuilding serves as a productive metaphor for archaeological practice as it:

“deeply resonates with archaeological interpretation; archaeologists bring together environmental data, zooarchaeological assemblages, evidence of trade and foodways, osteobiographies, architectural remains and all other textual and material traces to generate tableaux holistically.”

While there have been initial discussions of the integration of worldbuilding techniques into archaeological practice (Perry et al. 2025), pedagogical practice (Morgan 2025; Mol et al. in press) and an outstanding contribution in the form of a storyteller’s guide (Tyrrell & Simonen 2025), practicalities of worldbuilding in archaeology still do not impact practice at the point of data generation, and are not translatable for greater reuse. To this end, Colleen Morgan, Aris Politopoulos, Kathryn Killackey and Stuart Eve developed an analogue archaeological worldbuilding game, *And What Remains*, and trialled this game at the 2025 Theoretical Archaeology Group (TAG) meeting in York. Before testing, the project underwent the ethical approval process in the Department of Archaeology, University of York. This paper describes the process of creating the game, the results of the player testing, and future plans for the project.

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## 259. A virtual journey to the past: serious games as tool for public engagement with prehistoric heritage

*Xavier Roda Gilabert (Universitat Autònoma de Barcelona)*

*Susana Vega Bolívar (Universitat Autònoma de Barcelona)*

*Jorge Martínez-Moreno (Universitat Autònoma de Barcelona)*

*Rafael Mora Torcal (Universitat Autònoma de Barcelona)*

Archaeology is a critical tool for the interpretation of material culture and the reconstruction of past human behaviors and social dynamics. However, the discipline continues to face persistent challenges, including the fragmentary nature of the archaeological record, the complexity of analytical procedures, and the difficulty of communicating specialized knowledge to non-expert audiences, who often retain simplified, idealized or even mythical perceptions of the past (Renfrew & Bahn, 2005; Holtorf, 2005).

In this context, Information and Communication Technologies (ICT) have gained strategic relevance. Although they have been substantially implemented in museums and exhibition settings, they are still rarely used in active archaeological sites, despite a growing body of literature demonstrating their value for cultural mediation, public engagement, and the renewal of heritage communication models (Kalay et al., 2007; Cameron & Kenderdine, 2007).

Among emerging technologies, Virtual Reality (VR) is particularly noteworthy due to its immersive capacity, interactive nature and potential to dynamically integrate scientific data, visual resources and narrative structures. The incomplete, technically complex and difficult to understand nature of archaeological sites under excavation makes VR an especially suitable tool for enhancing the interpretation of archaeological processes. Key advantages include integrating real-world environments with digital overlays, adapting to visit formats, being flexible in evolving excavation contexts and significantly lower update costs compared to traditional museography.

These concepts are based on the long-term digital strategy developed at the Neanderthal site of Roca dels Bous in the southeastern Pyrenees in Spain. Since 2010, guided visits have incorporated handheld digital devices, making Roca dels Bous one of the first archaeological sites to use technology for mediation outside of museums (Vega, 2013; Roda Gilabert et al., 2013) (<https://larocadelsbous.uab.cat/es>). The project has established a stable model of interaction between archaeological research, digital experimentation, and public dissemination.

The Prehistopirineu Immers VR project (<https://prehistopirineu.com>) is the next step in this process, involving the development of a serious virtual reality game. Designed for use with VR headsets, the application offers users a first-person perspective on prehistoric life. It enables them to make decisions, solve tasks, and experience the environmental and technological constraints that shaped prehistoric societies. The educational value of serious games in cultural heritage contexts has been well demonstrated in terms of both knowledge acquisition and increased cognitive and emotional engagement (Anderson et al., 2010; Mortara et al., 2014; Andreoli et al., 2017).

This paper aims to present the digital content created, as well as exposing the implementation and evaluation of pilot experiences. The developed content combines interactive digital storytelling with real-time challenge solving. Users must follow simple instructions to obtain resources and confront challenges similar to those experienced by prehistoric communities. Created with the Unreal Engine 5 graphic suite, the virtual environments allow users to explore reconstructed natural landscapes and make decisions relating to subsistence strategies, tool production and social practices. Visual interfaces integrate scientific information seamlessly, avoiding the need for traditional exhibition formats based on textual panels. Tests carried out with different user groups, including schoolchildren, general visitors, university students, and local stakeholders, using questionnaires and interaction analysis, demonstrate that gamification enhances content retention and encourages active, experiential learning.

The use of digital tools and interactive media has made archaeological heritage more accessible and meaningful, linking scientific research with public

dissemination. The project demonstrates the efficacy of combining archaeology, ICT and gamification to overcome the traditional challenges of visibility and comprehension at prehistoric sites. Immersive environments promote a broader public understanding of archaeological research and create new cultural and economic opportunities in rural areas.

Keywords: gamification; virtual reality; serious games; archaeological heritage; knowledge transfer.

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## 303. Dust, Desire, and Discovery: Women, Archaeology, and their Representation in Games

*Dajana Ehlers (University of Cologne)*

The field of archaeology is represented in numerous video games. In some cases, the term is used explicitly, in most, it is implied. In videogames, the term often describes what would more accurately be considered looting. The majority of such characters are male (e.g. Nathan Drake from *Uncharted*, Indiana Jones in the associated games, or Gunther from *Stardew Valley*). The study described in this paper focuses on female archaeologists. In the study two female characters from a dating simulator are analysed and compared, each with either an archaeological or treasure hunter connection, alongside three characters from well-known franchises.

The most renowned archaeologist (that is actually a treasure hunter and is never called an archaeologist in the first games) is arguably Lara Croft. Her first appearance was in the original *Tomb Raider* (1996). As the protagonist of the series, she explores historical ruins, solves puzzles, and fights both human and animal adversaries, often using firearms. In the early titles, she wears her signature outfit: a crop top (showing a conspicuously large bust), short shorts, twin pistol holsters, and functional boots. She hails from an aristocratic family; her father was or is a scientist, and in some variations of the game, even an archaeologist himself. As one of the earliest female action

heroes in gaming, Croft remains a subject of considerable debate in contemporary discourse.

In 2009, Chloe Frazer appeared as a non-player character (NPC) in *Uncharted 2*. She is characterised as an action-oriented figure who can clearly be described as a looter. Due to her popularity, she received her own spin-off, *Treasure Hunter: The Lost Legacy* (2017), in which she takes on the role of the main protagonist, gaining emotional depth and complexity. Across the games, she is portrayed as intelligent, confident, independent, and competent.

The final character from a major franchise is Dr. Patricia Tannis from the first three parts of the *Borderlands* series. The player first encounters her during a mission at an abandoned excavation site, where she works as a (xeno-)archaeologist. In all her appearances, she remains an NPC, and her interactions with players are marked by social awkwardness. Within the games, she is portrayed as hyper-intelligent and morally ambiguous. From the first to the third instalment, Tannis undergoes a notable transformation: from an archaeologist deeply committed to her work and science to a treasure hunter acting ostensibly for the greater good of the universe.

These three characters are juxtaposed with Dolly the Dustbunny and Beau the Cardboard Box, two figures from the dating simulator *Date Everything!* Both are presented as potential romantic interests for the player. In the game, players can use special glasses to perceive and “humanise” household objects. Alongside the analysed characters, other examples include Able the Table and Conny the Gaming Console.

Beau is most likely a satire of Indiana Jones and Lara Croft. She is an explorer motivated purely by the thrill of adventure and the desire to uncover a “magical” or “historic” artefact hidden in the unexplored parts of the house. The player may accompany her on this quest. Dolly, by contrast, is a professor with a doctorate in prehistoric archaeology of Dustbunny. Her clothing presents an intentional paradox: she wears a bunny suit modelled after the

attire of Playboy Bunnies. Furthermore, her name and accent clearly allude to the singer Dolly Parton. This visual juxtaposition challenges expectations of how an academic professional “should” appear and behave.

This paper analyses how these dating-simulator characters parody well-known treasure hunters, how a seemingly oversexualised figure challenges the perception of archaeology and prejudices against women in science, and what statements about gender, science, and archaeological practice are made in games that deliberately play with stereotypes.

### 306. How do we want to play with the past? Authoritarian and democratic archaeology in contemporary gaming

*Ian Regueiro Salcedo (University of Ferrara)*

The representation of the past, whether in traditional archaeology, in mainstream culture, or in formal education, often follows an authoritarian top-down model. This approach is characterized by a non-reflexive way of viewing the past and an authoritative tone, where intellectual elites hold a “monopoly on truth in society.” It aims to present history as a single, certain “reality,” not as a selective representation. This preference for certainty can make historical understanding seem fixed or innate within the popular understanding of the past. In formal education, the strict adherence to textbook certitude encourages teachers to adopt an omniscient tone, which makes it difficult to deal with doubt or controversy. This way of thinking is prominent in media forms that privilege the authority of the narrator and treat the audience as a passive receiver, forming the basis of how cultural heritage has traditionally been portrayed and consumed.

In mainstream video games, this bias is clear in action-adventure triple-A games that deal with concepts related to the past — for instance, the *Assassin’s Creed* franchise —. These titles typically tell specific, authoritarian, and



satisfying reconstructionist stories that associate history with objective linear retellings, where players are given the opportunity to play like a god. Since these games are highly popular but offer only one main narrative path, they are the closest to traditional ideas of empirical history and archaeology, limiting the player's ability to question or change how the past is perceived. This is also true for commercial archaeological video games such as the Tomb Raider franchise and the Indiana Jones video games, where there is no room for player decisions in the main character's interpretations, which are almost always conclusive and fixed.

This research proposes that some contemporary independent video games can support a more democratic and accurate theoretical approach to archaeology. The selected games for this study have been *Return of the Obra Dinn* (Lucas Pope, 2018), *Heaven's Vault* (Inkle Studios, 2019), *The Forgotten City* (Modern Storyteller, 2021), and *Pentiment* (Obsidian Entertainment, 2022). These games challenge the authoritarian model by integrating, consciously or not, core concepts from modern archaeological theories into their actual gameplay mechanics. Furthermore, the video game medium is well suited to this shift due to its inherent support for archaeology-like mechanics such as the collection and organization of in-game information, which implies choosing which objects or information to collect.

The democratic shift relies on a deconstructive approach to history, recognizing that the past is not a fixed puzzle to be solved with right answers. Instead, the goal is to acknowledge the subjective nature of historical representation and preserve the openness and ambiguity of the past as a multiplicity of "pasts." This view aligns with game developers who often describe the past using multilinear narratives and systems, contrasting sharply with traditional archaeologists who focus on linear narratives and known outcomes.

Non-linear storytelling and mechanics related to player interpretations are key aspects of this change. Games that use branching structures formalize

archaeological concepts like interpretive openness by choosing different outcomes. For example, by using non-linear narratives these games evoke the idea that history is constructed and layered, rather than existing as a fixed timeline. Furthermore, this approach fosters a decentralized form of agency that reveals the enduring power of small actions to play a co-constitutive role in producing archaeological narratives.

By embracing uncertainty and curiosity, these deconstructionist games fundamentally shift players' roles from passive observers to active interpreters. The strategic use of non-linearity allows for creative and multi-perspectival engagements with the past. Players are frequently required to engage in "do-it-yourself" storytelling and to fill gaps based on the limited information they find. When players are forced to interpret evidence, they must exercise self-reflexivity and gain awareness of the subjective construction of past understanding. This process acts as an "empty mechanism" that focuses on constantly interrogating authority within the games.

Ultimately, by rewarding players who ask, "whose version of the past, and who gets to decide?", these titles become a guideline for future archaeogames. They demonstrate how the medium can translate complex theoretical ideas of anti-authoritarian archaeology into an interactive practice toward a deconstructive historical engagement.

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## 340. Pixels, Perspectives, and the Past – Diversity in historical game settings

*Charlotte Tornes (University of Cologne)*

### 1. Introduction

Traditional 3D heritage reconstruction often favors Technological Reductionism, focusing on geometric fidelity while neglecting the expression of period context and cultural semantics. Since the vitality of heritage lies in the practices surrounding it (Smith 2006), retrieving associated social memory is paramount. Large-Scale Virtual Reality (LBVR) exhibitions offer a powerful platform for heritage storytelling, but their focus on embodied experience and spectacle reignites a core controversy within Archaeogaming: how to balance the appeal of entertainment with the rigor of historical research?

Using the LBVR exhibition of the Wukang Mansion as a case study, this paper proposes and implements the "Interpretative and Atmospheric Reconstruction" framework. This methodology integrates multimodal source analysis and curatorial transparency to harmonize archaeological evidence with immersive experience. The research demonstrates the complementary relationship between historical scholarship and artistic creation, revealing how they coalesce to mitigate the "fun-versus-knowledge" dichotomy and effectively reconstitute the social memories linked to heritage.

### 2. Framework and Methodology

The Wukang Mansion (1924, architect László Hudec) symbolizes early urban modernity in Shanghai. Its era, the city's "Golden Age," saw the rapid development of consumer culture and global trade networks, where apartment buildings—as commodities—shaped new urban lifestyles. Today, however, the Mansion is often reduced to a photographic icon, its deeper social

memory left uninherited. The exhibition seeks to restore the unique significance of this architectural heritage by virtually reconstructing the apartment scene and daily life of the "Golden Age" in a virtual environment.

The project adopted the Interpretative and Atmospheric Reconstruction framework to balance scholarly rigor and user experience.

#### 2.1. Interpretative Reconstruction and Three-Tiered Evidence

Interpretative Reconstruction addresses missing direct evidence by proposing clearly marked hypothetical reconstructions (e.g., interior furnishings and daily objects) based on analogical materials. Following the ICOMOS Digital Heritage Framework and the Seville Principles (ICOMOS 2017), the process utilizes three categories of historical sources:

1. Category I (Directly Observable Evidence): Used to directly constrain geometric structure and scale (e.g., exterior facade, overall layout).
2. Category II (Documentary & Archival Evidence): Used to deduce floor plans and critical spatial elements (e.g., blueprints, period surveys).
3. Category III (Analogical & Interpretative Evidence): Used—under strict annotation—for the imaginative completion of interiors, lighting, and soundscapes, drawing from sources like non-fiction literature and oral history fragments.

#### 2.2. Atmospheric Reconstruction and Implementation

Atmospheric Reconstruction focuses on rebuilding the sensory dimensions of the era—light, color, soundscape, and social rhythm—drawing from Richard Wagner's concept of "Gesamtkunstwerk" (Total Work of Art). This requires integrating cross-disciplinary perspectives (e.g., art, fashion, and film history) with perceptual design elements. Moderate surrealistic expression is also employed to enhance psychological fidelity.

The exhibition uses a 150 square-meter free-roaming venue. Content is integrated via Unreal Engine and uses SLAM technology for multi-user exploration. Interactions are lightweight and diegetic, encouraging audiences to reveal historical layers by triggering dialogues or retrieving objects.

Crucially, the exhibition features Curatorial Transparency. In a post-virtual area, elements are explicitly marked using "Source and Script" tags, clarifying which parts are direct restitution, archival inference, or analogical hypothesis. This mechanism mediates between authenticity and integrity, reserving space for critical scholarly reflection while maintaining immersion.

### 3. Results: Empirical Validation

Since launch, the exhibition has welcomed over 500,000 visitors. An analysis of 300 valid public reviews collected early in the period preliminarily validated the methodology:

The project garnered an overall positive rating of 89.29%. Audience motivation was diverse, highlighting the project's cultural and experiential appeal: 33.33% were culture/history enthusiasts, followed by VR novices (28.89%). The word cloud analysis shows high-frequency mentions of "IMMERSIVE / PRESENCE" co-occurring with "KNOWLEDGE / LEARNING" and "HUDEC". The radar chart shows high scores for Narrative Depth (7.7), Psychological Presence (7.4), and Visual/Detail Fidelity (7.2). These results demonstrate that sensory cues (high immersion) and narrative structure (high depth) coalesced to form the audience's spatio-temporal perception, stimulating interest in historical knowledge.

### 4. Discussion and Conclusion

The Wukang Mansion LBVR case provides crucial pathways for rethinking the "fun-versus-knowledge" dichotomy in archaeogaming.

First, our findings show that immersive play and historical learning are mutually reinforcing. Empirical data reveals high scores in Narrative Depth and Psychological Presence co-occur with high-frequency mentions of "KNOWLEDGE / LEARNING". This substantiates the argument that when Atmospheric Reconstruction (appeal) is underpinned by Interpretative Reconstruction (rigor), embodied play enhances the acquisition of historical context, establishing LBVR as an effective medium for fostering historical empathy.

Second, Curatorial Transparency is the essential mechanism for addressing academic rigor. By marking the boundaries between restitution and hypothesis, the project legitimizes the use of Category III sources without compromising immersion. This transparency prevents the digital reconstruction from descending into Technological Reductionism and effectively encodes uncertainty into the encounter, preserving space for critical scholarly reflection.

In summary, the Interpretative and Atmospheric Reconstruction framework offers a compact and replicable model for the digital regeneration of complex heritage. It emphasizes that the synergy between a layered evidence system, perceptual control (via Gesamtkunstwerk), and focused Diegetic Interaction is required to achieve the poetic re-activation of social memory. We conclude that the LBVR platform is not merely a vehicle for spectacle but a didactic digital field (Pink 2007) that stimulates continuous reflection on the historical questions of "what we know, how we infer, and how we feel."

### Reference

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## 391. The Poetics of Reconstruction: An Interpretative and Atmospheric Framework in Virtual Heritage and its Contribution to Archaeogaming—The Case of Wukang Mansion LBVR Exhibition in Shanghai

*Jiahao Yan (Shanghai Jiao Tong University)*

*Huaqing Huang (Shanghai Jiao Tong University)*

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## 448. Echoes from Earth: Exploring Archaeology Through Play

*Lava Mohamad (University of Cologne)*

### Introduction

Digital games offer unique ways to explore archaeology by allowing players to interact directly with objects and environments from the past, creating a more engaging and memorable learning experience. This paper presents *Echoes from Earth*, an Archaeogame developed by a multidisciplinary group of students, which enables players to discover and examine artifacts from different historical periods in Cologne, Germany, from the perspective of an alien archaeologist sent to earth to study human civilization.

I also discuss the challenges and implications faced in the process of creating this game, including representing the city's complex history with limited archaeological artifacts, highlighting key questions about how digital games can present the past in a way that is both responsible and engaging, carefully balancing educational goals with the need to respect historical complexity and avoid oversimplification or misrepresentation.

### Methods and Materials

The game uses a narrative-driven approach to guide players through Cologne's archaeological history. Players explore a virtual environment representing the city and discover artifacts from different historical periods, including Roman, Medieval, and modern times. The story provides structure to this exploration, framing each discovery as part of a larger journey to understand human activity over time.

Unity with C# was used for programming, handling character movement and actions within the game. Pixel Art was used to design characters, artifacts, buildings, and environments, with some assets adapted from free online resources. Sound and music were produced using Audacity and AI tools, combining effects and background tracks for the game's atmosphere.

Design decisions, such as how artifacts are presented, how players can examine them, and how environments are built, were based on intensive research to ensure that all objects and details are represented as accurately as possible. Each item reflects its real-life appearance, purpose, and historical context, including materials, shapes, colors, and uses, as well as the appearance of buildings and surroundings.

### Results

The game successfully creates an interactive environment where players explore Cologne's history through the eyes of an alien archaeologist. Players can examine artifacts closely and engage with quizzes and mini-games that test their knowledge, then provide accurate historical information about each item. Artifacts can also be sorted into their respective time periods—Roman, Medieval, or modern times, allowing players to learn about the city's history, culture, and technological developments.

### Discussion

Starting with the simple and fun idea of an alien archaeologist exploring Earth, the development of the game revealed many challenges and important questions about representing the archaeology of a historically significant city with only a limited number of artifacts. Decisions had to be made about whose perspective of history should be shown and how to present it meaningfully? Which artifacts should be included, and which should be left out? And what aspects of the past should be represented within the game?

Difficult choices had to be made that would strongly influence how players interpret both archaeology and the city's history. As a student project with limited time and resources, only a small part of these possibilities could be explored, leaving plenty of space for future improvement. Nevertheless, the collaboration of an interdisciplinary team was very helpful, bringing together different skills and perspectives to answer these questions and create an engaging, interactive, and educational experience.

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## Friday

### S7: Reframing the Past: Cognitive, Psychological, and Computational Approaches to Interpreting Artefact Function

*Silvia Stein, Independent Researcher and active EAA and CAA member*

*Stefan Zechner, Technische Universität Wien, Technische Physik, Faculty Member*

*Sergei Makhin, Clinical Psychologist and Docent at V.I. Vernadsky Crimean Federal University, Ukraine*

**Location:** Hörsaal 05

**Session Format:** Standard

This session seeks new ideas in archaeology for re-describing alternative artefact function though we also welcome new ways in which computational methods, can inform 1. cognitive processes, 2. brain evolution, 3. intellectual evolution, and 4. tool function. An example is the new idea that 100-72 thousand years old (kya) punctured shells not only had ornamental value, they had a functional value as fishing tools. “Interpreting shells found in archaeological contexts is not straightforward. They can be food remains, personal ornaments, or objects used in “black magic” (cf. Léo Neto et al. 2012); fishing nets (cf. Stein and Pacheco 2025); and counting devices (cf. Overmann 2016)” (Mouclier, et al, 2025). This re-description of punctured shells as fishing tools for nets has more explanation power than the evolution of the parietal lobe occurred in relation to early use of string in fishing, shell weights and ornaments 115 70 kya (Stein & Pacheco, 2025), besides the role of the bow and arrow, about 80 kya (Lombard, 2025).

This session invites contributions that explore how archaeology or cognitive science, psychology, neuroscience, and computational methods can enrich

our understanding of artefact function in past societies. Traditional interpretations often emphasize symbolic or ritual perspectives, we cannot “resort to this explanation when they do not understand a feature” (Marchand, et al, 2021). An example is the symbolic description of punctured shells as ornamental necklaces and headbands, when a new functional fishing use or re-description has been tested with computer imaging and experimental reconstruction of a fishing net weight system, establishing that brain parietal lobe evolution preceded by 40,000 years the brain evolution associated with the bow and arrow (Stein & Pacheco, 2025, & Lombard, 2025).

This session promotes work in cognitive and experimental archaeology (Bruner, 2020, Stout, et al, 2017, Wadley, 2024, & Wynn, et al, 2024,) integrating the role of artefacts into models of the evolution of human perception, motor coordination, memory, and decision-making.

The session seeks to question established interpretations of artefact function, though we also welcome papers on how computational and quantitative approaches like digital imaging and use-wear provide new insights into cognitive, visual, motorial and spatial processes. We are interested in how these processes underly tool use, production, and perception. For example, neuroarchaeological approaches link brain regions such as the precuneus to complex tool-related activities (Bruner et al., 2018 & Lombard, 2024), while agent-based modeling and machine learning can help evaluate alternative scenarios of artefact function (Eleftheriadou, et al, 2025)- Similarly, computer modeling, digital photo editing, VR/AR environments, and eye-tracking experiments have been employed to investigate how artefacts afford certain behaviors and how perception shapes functional interpretation (Stout & Hecht, 2017; Bruner, 2017).

We particularly encourage contributions that:

- Use experimental archaeology combined with computational or quantitative analysis to test functional hypotheses.
- Apply neurocognitive or behavioral frameworks to reinterpret artefact functions.

- Demonstrate how visualization tools and synthetic reconstructions (e.g., digital “synthetic memories”) can shift interpretative paradigms (Stein & Pacheco, 2025).
- Explore bias detection and reflexivity in archaeological interpretation through digital media or quantitative analyses such as use-wear.

Bringing together diverse approaches, this session seeks to show how artefacts can be understood as products of both material and cognitive processes. Our scope is to create a dialogue that situates archaeological evidence within broader models of human evolution, highlighting how computational and quantitative methods can inform questions in psychology and neurosciences regarding cognition, perception, and motorial function, and not merely address the issue of the symbolic value of an artefact when archaeologists “do not understand a feature” (Marchand, et al, 2021).

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Western New Guinea: Ethnographic and Archaeological Perspectives. *Ethnoarchaeology*, 1–38.

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|               |                                                                                                                                                                                                                                                  |
|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 11:50 – 12:10 | 104. Establishing a Functional Use for the MSA Engraved Blombos Ochre Through Image Based Vectorization, Use Wear Constraints, and Experimental Reconstruction<br><i>Silvia Stein (EAA); Morris Chukhman (University of Illinois at Chicago)</i> |
| 12:10 – 12:30 | 102. Tracing the Mind of the Maker: Cognitive Expressions in the Rock Art of Panchmukhi, India<br><i>Prity Rawat (Banaras Hindu University)</i>                                                                                                  |
| 12:30 – 12:50 | 130. An Early Decision-Making Record from the Cave Zaraut-Kamar at Uzbekistan: A Cognitive Interpretation of a Neolithic Rock Painting<br><i>Janusz Krukowski (Independent)</i>                                                                  |
| 12:50 – 13:00 | Discussion                                                                                                                                                                                                                                       |

## 102. Tracing the Mind of the Maker: Cognitive Expressions in the Rock Art of Panchmukhi, India

Prity Rawat (Banaras Hindu University)

Art has been an essential instrument of humanself-expression and prehistoric painting is a critical source of insight into the mental realms of the early humans or we can say that rock art provides an in-depth insight into the cognitive development of the prehistoric society and how early man perceived, represented, and engaged with his surroundings. The paper explores the Panchmukhi rock art site which is located on the top of the hillock of Robertsganj near to Churk road of the Sonbhadra district, Uttar Pradesh, to draw an insight on how people of the ancient times developed cognition and symbolic thinking. There are 33 shelters, in which 23 found painted and most of them are facing south. J. Cockburn was the first one who documented it and later G. R. Sharma did some work on it. Later A. K. Narayan amd P. C. Pant had exprolerd the mentioned area with different perspectives of archaeology. Scholars like Jagdish Gupta published illustrations which includes peacock hunting, female figures, archers and so on from the paintings of Punchmukhi. Also the scholars like Rakesh Tewari, Yashodhar Mathpal and Sachin Kumar Tiwary had done some landmark works on this region. This site has many panels depicting people, animals, hunting episodes and geometrical patterns. The forms selected, the figures' space arrangement, and the repetition of themes of animals, humans and ritual scenes point to the changing perceptions of abstraction, identity and communication.

Placing the Panchmukhi rock art into the larger conceptual framework of cognitive archaeology, the paper will focus on artistic expression as a tool of thought and social expression that connected the behavioural patterns of survival to the symbolic imaginative realms. The current paper will attempt to delve into the intellectual aspect of such artistic statements- to follow the way the ancient mind perceived, conceptualized and rendered its surroundings. The studies answer some questions: What can the Panchmukhi

paintings tell us about the psychological structure of their artists? Is it possible to recognize developmental patterns in the cognitive complexity in terms of change of artistic style and technique matter over time?

The research relies mostly on field information in terms of capturing photographs, digitizing it and observing the location at Panchmukhi. There are also ethnographic parallels on the use of tribal art that has been used to realize symbolic persistence and continuity on perceptions. Theories of cognitive archaeology and neuroesthetics inform the cognitive framework of the research, with perception, pattern recognition, and symbolic communication being the most important indicators of becoming cognitive.

The initial examination shows that there was a strong correlation between the artistic complexity and spatial structure between periods of the Panchmukhi site. Initial layers represent simple geometrical and linear shapes, but subsequent panels of more organized compositions of human-animal interaction, ritual postures and group action - both of which are signs of higher-order thinking. Clustering aided by machines produced different families of motifs (circular enclosures, hunting processions, composite figures) that indicated the repetitive symbolic purpose of the expression, not casual. The changes in style, such as the use of controlled line and narrative grouping, lead to the greater cognitive elaboration and development of collective memory. The data also indicate the different emphases of perceptions - external observation of nature to the introspective and conceptual visualization.

Such results add to an accumulating knowledge of the way in which prehistoric art captures human cognition development. This paper will collaborate both the archaeological field information with digital analysis to demonstrate art as an aesthetic and neurological product of the changing consciousness. In addition to archaeology, such approach provides a benchmark to interdisciplinary studies presented by art history, neuroscience, and artificial intelligence. It also confirms the significance of the regional locations,

such as Panchmukhi, as part of the greater South Asian rock art tradition, and makes it clearly why they should be relevant in international debates on the beginning of symbolic thought.

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## 104. Establishing a Functional Use for the MSA Engraved Blombos Ochre Through Image Based Vectorization, Use Wear Constraints, and Experimental Reconstruction

*Silvia Stein (EAA)*

*Morris Chukhman (University of Illinois at Chicago)*

Engraved ochres from Blombos Cave (southern Cape, South Africa) include cross hatched geometric motifs dated to the Middle Stone Age Still Bay/M1 sequence (c. 75–77 ka), and are typically treated as early geometric representations and/or evidence for symbolically mediated behaviour (Malafouris, 2021). Perforated *Nassarius kraussianus* shells from the same site have likewise been interpreted primarily as personal ornaments on the basis of morphometric and use wear analysis (Stein & Pacheco, 2025). Building on prior exploratory work that raised a functional alternative for punctured shells as string borne net weights (Stein & Pacheco, 2025), this paper focuses

on the engraved ochre and evaluates two competing hypotheses: (H1) the cross hatched motif is a procedural template that encodes a diamond mesh netting operation; (H0) the motif is non procedural (decorative, symbolic, or incidental) and will not support a constraint satisfying reconstruction.

We define “retroactivity” in methodological terms as a retrodictive workflow: using present material traces to constrain plausible past technical actions by iterating between (i) high resolution documentation, (ii) digital abstraction into measurable geometries, and (iii) controlled experimental reconstruction. This is an inferential use and follows material engagement accounts (material engagement theory) of mark making as traces of action and skill (Malafouris, 2021), alongside best practice cautions about the inferential limits of experimental archaeology (Wadley, 2024).

Methodologically, we implement a reproducible computer assisted pipeline: (1) macro photography of engraved surfaces (including focus stacking to increase depth of field where appropriate), (2) tablet based re tracing of incisions guided by published microscopic descriptions, (3) semi automatic raster to vector conversion of traces into scale calibrated polylines to enable metric analysis (cf. vectorization workflows in document digitization), and (4) quantitative motif analysis, including circular statistics of line orientations, coefficients of variation for inter line spacing, intersection graph topology, and unit cell segmentation of the repeated lozenge elements. These metrics parameterize candidate net reconstructions (rope diameter; mesh angle/spacing; single mesh versus trammel configurations), which are then assessed for mechanical plausibility under tension and weight bearing and for robustness to measurement uncertainty.

Preliminary results from the vectorized dataset indicate low variance in diagonal orientations and repeated unit geometry consistent with deliberate patterning, and they reduce the space of plausible “weaving operations” to a small set of reconstructible procedures. In the full paper we report quantitative pattern statistics, reconstruction outcomes, and explicit decision criteria that would falsify H1 (e.g., inability to reproduce the motif under feasible knotting constraints; non robustness to uncertainty; superior fit of the same data to alternative non procedural models).

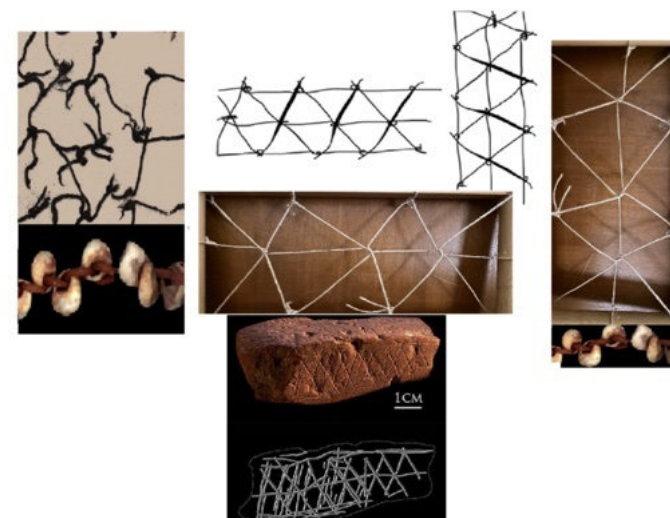


**Figure 1.** Workflow linking the Blombos engraved ochre to a replicable reconstruction test. Bottom: published photograph of engraved ochre piece M1–6/8938 (Blombos Cave, ~75–100 ka) and tracing of incision paths after prior descriptions of the motif and its production (Malafouris, 2021). Top: this study’s tabletbased retracing that isolates the proposed stroke order and unit geometry, followed by geometric rectification (rotation/deskewing). Centre/right: physical string model built from the same unit geometry to evaluate whether the motif functions as a procedural template for constructing a diamondmesh (trammelstyle) net under realistic constraints. Insets: punctured *Nassarius* shell beadwork from the broader Blombos assemblage as a plausible weighting/attachment analogue (Stein & Pacheco, 2025). Tablet tracing produces a layered, scalereferenced raster drawing that can be exported and vectorized into polylines, providing an auditable bridge between the archaeological surface and the experimentally woven artefact.

Beyond the Blombos case study, the contribution to CAA is methodological: a transparent, portable vectorization and measurement workflow for engraved artifacts that produces reusable vector datasets (SVG/GeoJSON) suitable for comparative analysis, catalog updates, and future machine assisted pattern classification.

## Discussion

The principal methodological risk in functional interpretations of early engravings is that the argument remains at the level of visual analogy. The tablet drawing plus vectorization workflow (Fig. 1) is designed to convert a resemblance claim (“it looks like a net”) into a reproducible, falsifiable



modelling exercise by (a) stabilizing the proposed geometry as data and (b) deriving explicit, checkable predictions for experimental reconstruction.

Tablet tracing is used first because it supports controlled replication of the engraving's stroke order and spatial constraints while preserving an audit trail. Working from scale calibrated photographs, the tracing separates individual incisions into layers, records the sequence of line production (as inferred from intersection relationships and stroke order analyses; Malafouris, 2021), and enables systematic transformations (rotation, scaling, and de skewing) without changing the underlying relationships among intersections. This step converts a small, irregularly preserved surface into a shareable working drawing that can be inspected and re traced by other researchers.

Vectorization then converts the tablet raster into scale calibrated polylines (e.g., SVG/GeoJSON) suitable for quantitative analysis. Once the motif is represented as vectors, it becomes straightforward to compute segment orientations, intersection topology, mesh aspect ratios, and spacing statistics, and to compare those metrics against competing procedural models using the same error criteria. Because vectorization is now a standard component of image analysis pipelines (including automated and semi automatic approaches), the intermediate data products are portable and can be archived alongside the photographs to support replication.

Crucially, the vector model also acts as a parametric "pattern piece" for building and testing the physical net. Intersection points translate into candidate knot locations; unit cell dimensions constrain string length and tension; and the presence/absence of a central "trammel" line yields clear predictions about load transfer and deformation under weights. The experimental reconstruction phase therefore functions as the empirical check on the computational interpretation. If the engraved geometry is a usable template, the reconstructed mesh should be buildable under realistic constraints (string thickness, tension, and weight loading) and should exhibit the proposed functional behavior. If it is not, failure modes—unstable intersections,

inconsistent mesh spacing, or non viable loading—provide direct grounds for rejecting or revising the hypothesis, consistent with current calls for explicit controls and constraint based inference in experimental archaeology (Wadley, 2024).

The implications are the occupants of the MSA BBC not only had intellectual capacities to design, record, make and re-use string based nets, they had developed superior finger dexterity with refined engineering net construction capacities. Simultaneously MSA expansion of the parietal lobe, and precuneus, in coastal areas, involved in spatial thinking occurred. Future EEG research of modern humans mirroring the mark and net making meaning process can test for an artefact's influence on meaning making (retroactivity) bringing humans to consciousness.

In sum, tablet drawing and vectorization do not replace interpretive judgment; they constrain it, document it, and make it testable by turning a motif into a measurable object and a reconstruction into a repeatable protocol.

#### Keywords

Blombos Cave; engraved ochre; vectorization; computational motif analysis; experimental archaeology; nets; material engagement theory.

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### 130. An Early Decision-Making Record from the Cave Zaraut-Kamar at Uzbekistan: A Cognitive Interpretation of a Neolithic Rock Painting

*Janusz Krukowski (Independent)*

Keywords: Zarautsoi Rock Paintings, semasiographic writing, Neolithic Rock Painting, decision-support system, graphic analysis

#### Introduction

The simplest procedure for equitably dividing a resource between two individuals is as follows: one divides the resource into two parts, and the other chooses one of them. Both individuals are interested in owning a share of the resource; both have equal rights to the resource; the resource is divisible without loss of value. However, even in the Neolithic period, there was a need for a decision-support system, particularly crucial for allocating resources necessary for survival while simultaneously preventing the generation of dangerous conflicts. A graphic representation of such a system can be seen on the wall of the Zaraut Kamar Cave in Uzbekistan.

#### Materiality - "Zarautsoi Rock Paintings" in Uzbekistan

In the Republic of Uzbekistan, 30 kilometers from the city of Sherabad, in the Zarautsoi Gorge, there is the UNESCO World Heritage Site "Zarautsoi Rock Paintings" inscribed on the UNESCO World Heritage List in 2008 (<https://whc.unesco.org/en/tentativelists/5299/>). These painted graphics may have been created as early as the Mesolithic period, or perhaps at the turn of the Mesolithic and Neolithic. Among these graphics of humans and

animals is one mysterious symbol – a dotted oval, divided vertically into two halves. Scholars typically attribute it to a shamanic or sacred meaning, but there is no evidence to support this.



Drawing based on a photograph by A. Rozwadowski (2007, p. 404, photo 2)  
Dimensions: width 27 cm, height 38 cm.

Some scenes depicting people in triangular robes are believed to be hunting scenes, with hunters approaching the herds disguised as large birds. A similar oval, dotted graphic was traditionally painted on their stone and clay huts by Tajiks (people of Persian origin), who believed this was a symbol of the joyful Muslim holiday of Nowruz (Rozwadowski A. 2007, p. 402).

#### Methodology – Comprehensive Analysis

1. The oldest and most distinctive graphic from this site is a composition of three scenes, drawn in black, depicting a total of 24 human figures, 3 dogs, 3 aurochs, 1 female aurochs, and 1 gazelle. Beside, there is a red oval with 20 dots, divided into two halves of 10 dots each.

In these three adjacent scenes, as many as 18 graphic silhouettes appear in voluminous cloaks, giving their figures a triangular shape, considered "bird-like." These individuals are armed with short weapons – staffs or goads. Such weapons are unsuitable for hunting on the steppe, especially on foot (horses are not depicted in the drawings). Such short weapons can only be used for close-range defense or for herding cattle. The remaining six individuals lack triangular capes, but they are archers and spear throwers. A total of nine arrows/darts are visible, but none of the animals are wounded. A

quantitative comparison of the people and weapons indicates these are scenes of animal capture for domestication, not hunting. The flowing capes and short sticks are shepherding tools, not hunting weapons.

2. For Neolithic herders, cattle constituted their most valuable asset, which, under certain circumstances, had to be divided among equal shareholders—partners or heirs. Therefore, for mutual benefit, a decision-making system is developed to support the division process – one shareholder divides the herd, while the other chooses one of the allocated shares. To emphasize the importance of this decision, it is painted on the cave wall - a location sheltered from rain, highly visible, and frequently visited.

3. The speckled and divided oval can also be read as a sequence of digital arithmetic operations, which we would now write as " $20/2 = 10$ " and " $20-10 = 10$ ." The meaning of the arithmetic operations described here is entirely secular, simple, and understandable, both to us, in the Digital Era, and to Neolithic people.

#### Results - Conclusions

1. Three graphics forming a single composition depict the capture of animals for breeding purposes.

2. The graphic oval, speckled sign in the Zaraut Kamar cave represents the fair division of a herd of cattle between two entities with equal rights. It is therefore a record of a basic decision-support system for cattle division.

3. The number of dots in the oval indicates the number of animals in the divided herd. The decision to peacefully divide the herd is mutually beneficial and was recorded on the rock as a model for division procedures, intended to prevent future conflicts.

4. The spotted and divided oval represents a semasiographic mark, so-called graphemes. Graphemes are units of semasiographic writing that are not associated with any language.

5. The speckled oval is a graphic symbol of purely instrumental, utilitarian nature, an element of decision-making system; it does not refer to concepts considered as unscientific (like shamanism or religion).

6. The local cultural code survived for thousands of years among successive pastoral peoples living in the same conditions and in the same area of present-day Uzbekistan, undergoing subsequent transformations and ultimately becoming a symbol of the Nowruz holiday.

#### The Research as a Starting Point for Discussion

The spotted graphic oval symbol, conveying a specific and complex concept, is not an image of any precise object, but an expression of an abstract idea. Semasiographic writing conveys concepts without the intermediation of linguistic structures. Today, it takes the form of road signs, musical notation, mathematical symbols, and various other signage graphic systems. Not everyone recognizes it as writing, but everyone uses it, including the illiterate. The abstract meanings of ancient rock graphics, previously perceived as figurative representations, certainly require in-depth research.

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## S9: AI Applications in Cultural Heritage and Archaeological Protection

*Dante Abate, ERATOSTHENES Centre of Excellence*

*Fabio Remondino, Fondazione Bruno Kessler*

*Donna Yates, Maastricht University*

*Hector A. Orengo, Barcelona Supercomputing Centre*

**Location:** Auditorium Maximum

**Session Format:** Standard

Illicit excavations and the trafficking of cultural property remain serious transnational threats, often linked to organized crime and conflict-related instability. Addressing this challenge requires interdisciplinary collaboration and the integration of innovative digital tools. Artificial Intelligence (AI) and Machine Learning (ML) are emerging as game changers in this domain, enabling the processing and analysis of vast and complex datasets at unprecedented speed and accuracy. These technologies can rapidly identify, classify, and monitor archaeological features and artifacts across extensive spatial and temporal scales, enhancing early detection and response capabilities. Such analytical power is particularly valuable in countering the growing challenges of illegal excavations and the illicit trafficking of cultural property, where timely insights can make a decisive difference in safeguarding heritage assets.

This session invites contributions from researchers, heritage professionals, law enforcement agencies, technologists, and policymakers working on AI- and ML-driven approaches to cultural heritage protection.

To ensure thematic clarity, submissions should align with one or more of the following sub-strands:

- remote sensing and site detection,

- artifact recognition and provenance analysis,
- predictive modelling of looting risk,
- integrated monitoring and early warning systems.

Contributors are requested to report validation methods, datasets, metrics, and limitations to ensure methodological transparency and comparability. A diversity and inclusion statement is encouraged, and mechanisms to broaden participation (such as cross-regional partnerships, involvement of early-career researchers, and engagement of underrepresented groups) are strongly supported. Finally, all submissions should include an explicit section on ethics and safeguarding, addressing data sensitivity, potential dual-use risks, and responsible disclosure, thereby ensuring that technological innovation proceeds with full consideration of cultural, legal, and societal responsibilities.

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**14:00 – 14:20** 142. A Geospatial Machine Learning Approach to Predict Illicit Excavation Risk: A Case Study from Archaeological Sites in Northern Sri Lanka  
*Milange Hansamali (Sichuan University); Herathmudi-yanselage Anuradha (Department of Archaeology); Janaka Prasanna (National Disaster Relief Service Center)*

**14:20 – 14:40** 194. “Drivers of Archaeological Looting in the Nile Delta: Leveraging Satellite Remote Sensing and Multilevel Modelling for Spatiotemporal Analysis  
*Michelle Fabiani (University of New Haven)*

**14:40 – 15:00** 370. Monitoring submerged cultural heritage: AI-driven detection of suspicious vessel activity over underwater archaeological sites using optical satellite images  
*Maria Cristina Salvi (Eratosthenes Centre of Excellence); Dante Abate (Eratosthenes Centre of Excellence); Iban Berganzo-Besga (Barcelona Supercomputing Center); Hector A. Orengo (Barcelona Supercomputing Center)*

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**15:00 – 15:20** 357. Can we detect ancient canals with AI: Leveraging big multitemporal multisource satellite data and deep learning to detect complex and invisible landscape features  
*Nazarij Bulawka (University of Warsaw); Hector Orengo (Barcelona Supercomputing Center); Felipe Lumbreras Ruiz (Universidad Autónoma de Barcelona); Iban Berganzo-Besga (Barcelona Supercomputing Center); Ekta Gupta (Landscape Archaeology Research Group (GIAP), Catalan Institute of Classical Archaeology)*

**15:20 – 15:40** 286. Introducing AI Chatbots for Remote Sensing Archaeology  
*Nicolas Melillos (Cyprus University of Technology)*

**15:40 – 16:00** 5. Uncovering Hidden Patterns in Ancient Gandharan Communication, An AI-Driven Approach  
*Muhammad Aftab (Zulekha International); Syed Shehzad Ali Shah (Auto Trader PK Group)*

**16:00 – 16:30** Coffee break

**16:30 – 16:50** 8. Detecting Media Clones in Cultural Repositories Using a Positive Unlabeled Learning Approach  
*Vasileios Sevetlidis\*; Vasileios Arampatzakis\*; Melpomeni Karta\*; Ioannis Mourthos\*; Despoina Tsiafaki\*; George Pavlidis\**  
  
*\* Athena Research Centre*

**16:50 – 17:10** 211. Transfer learning with ADAF: extending archaeological detection beyond its training ground

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| <i>Nejc Čož (ZRC SAZU); Luka Škerjanec (ZRC SAZU); Žiga Kokalj (ZRC SAZU)</i> |                                                                                                                                                                                                                                                                                     |
| <b>17:10 – 17:30</b>                                                          | 296. Popularising archaeological predictive modelling: An application on neolithic settlements in Thrace<br><i>Ilias Ladenis (International Hellenic University); Kyriakos Sgouropoulos (Democritus Univeristy of Thrace); Dushka Urem-Kotsou (Democritus Univeristy of Thrace)</i> |
| <b>17:30 – 18:10</b>                                                          | Discussion                                                                                                                                                                                                                                                                          |

### 5. Uncovering Hidden Patterns in Ancient Gandharan Communication, An AI-Driven Approach

*Muhammad Aftab (Zulekha International)*  
*Syed Shehzad Ali Shah (Auto Trader PK Group)*

This study applies natural language processing (NLP) and network analysis to explore the evolution of language and communication in ancient Gandhara (modern-day Pakistan and Afghanistan). We analyze a dataset of digitized inscriptions and texts from the 1st to 5th centuries CE, using AI tools to identify patterns in linguistic structures, cultural references, and technological influences.

Our research question focuses on how language and communication patterns reflect cultural and technological changes in ancient Gandhara. We employ NLP techniques, such as topic modeling and sentiment analysis, to extract insights from the texts. Our preliminary results indicate significant shifts in language use and cultural references, reflecting the impact of technological advancements and cultural exchange on human communication.

This study demonstrates the potential of AI-driven digital archaeology to uncover new insights into the past, informing our understanding of human communication and cultural evolution. By applying AI methods to cultural heritage data, we can preserve and promote the rich cultural heritage of the Gandhara region.

References:

- 1. UNESCO. (2003). Charter on the Preservation of Digital Heritage.
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### 8. Detecting Media Clones in Cultural Repositories Using a Positive Unlabeled Learning Approach

*Vasileios Sevetlidis (Athena Research Centre)*  
*Vasileios Arampatzakis (Athena Research Centre)*  
*Melpomeni Karta (Athena Research Centre)*  
*Ioannis Mourthos (Athena Research Centre)*  
*Despoina Tsiafaki (Athena Research Centre)*  
*George Pavlidis (Athena Research Centre)*

Digital repositories have become indispensable for cultural heritage research, providing large-scale access to artefacts while also introducing new curatorial challenges. One such challenge is the presence of duplicate or near-duplicate records: multiple images of the same vessel across publications, photographs of fragments under varying conditions, or stylistically similar artefacts that may inform reconstruction and distribution studies. Manual detection of these “clones” is both time-consuming and error-prone,



limiting the analytical potential of collections such as the AtticPOT repository, which documents thousands of Attic artefacts from ancient Thrace. We address this challenge by casting clone detection as a Positive–Unlabeled (PU) learning problem, a paradigm well aligned with cultural heritage repositories where a few certain positives (e.g., repeated images of a vessel) coexist with a large pool of uncertain candidates. Our method trains a lightweight Clone Encoder from a single anchor image per artefact, generating augmented views to simulate re-photography and preservation variability. The encoder operates on the latent  $\ell_2$  norm, learning a compact region for positives and an adaptive margin that separates them from the unlabeled pool. This results in a transparent, interpretable threshold that can be tuned by curators, enabling “find-similar” functionality, duplicate detection, and fragment attribution.

We evaluate the approach on two datasets: the general-purpose CIFAR-10 benchmark and the domain-specific AtticPOT repository (~6,000 artefact images). On CIFAR-10, our method achieves F1 = 96.37 (AUROC = 97.97), outperforming strong self-supervised baselines such as BYOL and MoCo. On AtticPOT, it reaches F1 = 90.79 (AUROC = 98.99), improving by +7.70 F1 points over the best baseline (Deep SVDD) under the same backbone. These gains are primarily due to substantial precision improvements, ensuring fewer false positives while maintaining high recall. Qualitative retrieval experiments further demonstrate stable similarity neighborhoods across viewpoint and preservation variation.

The proposed framework offers several advantages for digital heritage practice: it avoids the need for explicit negatives, integrates seamlessly into curator-in-the-loop workflows, and exposes a single interpretable operating parameter. Beyond clone detection, it can support record linkage, stylistic grouping, and exploratory research within AtticPOT and similar repositories. In conclusion, we demonstrate that PU learning provides an effective and practical solution for artefact clone detection in cultural heritage repositories. The method aligns with curatorial realities—scarce positives, uncertain negatives—and advances repositories from static catalogues toward intelligent research assistants. Future work will explore multimodal integration

with catalogue metadata, cross-collection validation, and deployment within large-scale infrastructures such as Europeana.

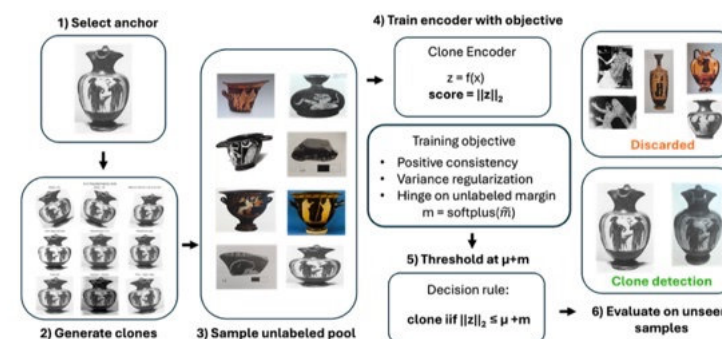


Figure 1: Per-query workflow. From a single anchor, augmented clones are contrasted against an unlabeled pool. A PU-trained encoder yields an interpretable norm threshold for curator-in-the-loop screening.

## 142. A Geospatial Machine Learning Approach to Predict Illicit Excavation Risk: A Case Study from Archaeological Sites in Northern Sri Lanka

*Milange Hansamali (Sichuan University)*

*Herathmudiyanselage Anuradha (Department of Archaeology)*

*Janaka Prasanna (National Disaster Relief Service Center)*

### Introduction

Cultural Heritage preserves the 'Cultural memories' of our ancient peoples. In the contemporary world, illicit excavation is one of the most dangerous threats to the preservation of cultural heritage. Artificial Intelligence (AI) is an immensely powerful tool for the preservation of cultural heritage, through monitoring and early warning mechanisms (Zhang,2022). Altaweel et al. operated AI with unmanned aerial vehicle imagery to identify illegally

looted heritage sites (Du, 2021). Machine Learning (ML) applications—including supervised, unsupervised, semi-supervised, and reinforcement learning—can be used to preserve cultural heritage (Lafta, 2025).

In the archaeologically dense North of Sri Lanka, this issue is particularly severe. The historical pillaging of 178 sites documented creates an issue of the necessity for efficient, resource-conserving conservation efforts without any delay. Satellite imaging is an applied technology, although ubiquitous, used to detect looting, yet its availability can be limited by price, resolution, and cloud cover. This research proposes a paradigm change: from reactive detection to proactive risk prediction. Using observed locations of Illicit excavation as a training dataset, this work develops a geospatial predictive model that forecasts areas that are likely to be at high risk of future Illicit excavation. The main research questions are: 1) What are the most significant predictors of environmental and socio-economic factors of archaeological site illegal excavating in Northern Sri Lanka? 2) Can a statistically robust model for creating a credible illegal excavating risk map of the region be devised? 3) Can the model be integrated into a successful, holistic monitoring system of heritage conservation?

### Methods and Materials

This study employs a case-control study in a geographic information system (GIS) and machine learning framework (ML). The model data were collected only from free, open, and available sources to render it reproducible and accessible. A case-control dataset was developed for the purpose of this analysis. The positive cases consisted of the 178 identified Illicit excavated archaeological sites across the study area. As a control, a random sample of 178 officially recorded, non-excavated archaeological sites were taken. A full suite of predictive factors was extracted from freely available geospatial data sources for each of the 356 sites.

These covariates represented key aspects of accessibility (distance to primary, secondary, and tertiary roads in OpenStreetMap), terrain (slope and ruggedness derived from SRTM elevation data), land cover (classified as forest, farmland, or urban and validated with Google Earth historical imagery),

population density (from WorldPop as a proxy for visibility and access), and proximity to authority (distance to nearest police station, military base, and archaeology office, obtained by manual geocoding). We used a logistic regression model, because that is easy to interpret and it can handle binary outcomes (i.e., excavated or not excavated). The dataset was divided into a 70% training subset and a 30% test subset. The model was trained to determine the optimal variables for separating excavated and non-excavated sites. Performance was quantified in terms of standard measures of performance, i.e., Accuracy, Precision, Recall, and F1-Score.

### Results

The predictive model performed well, reliably distinguishing between illicit excavated and non-excavated sites. This was quantitatively corroborated by an Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve of 0.84, indicating superb prediction ability. Variable importance analysis identified the most significant drivers of the risk of illegal excavating, wherein distance to secondary roads was the strongest predictor, and risk was greatest at moderate distances—a finding that suggests looters strategically balance access versus isolation. Furthermore, both low population density and greater proximity to police stations were strongly associated with a higher risk of illicit excavation, highlighting the critical factors of low visibility and diminished deterrence. Regarding land cover, agricultural and scrubland environments were significantly more vulnerable than those in dense forests or urban settings. The most important outcome of the research is an Illegal Excavation Risk Map of Northern Sri Lanka, classifying the landscape into high-risk, medium-risk, and low-risk zones. This map is an interactive visual tool enabling heritage authorities to offer effective prioritization of ground observation and conservation.

### Discussion

The findings confirm that illicit excavation is not a random activity but is strictly determined by a measurable interaction of accessibility, visibility, and deterrence. The model contradicts the impression that remoteness alone

equals security; instead, it highlights the focal risk of accessible but sufficiently distant areas from authorities. This research transcends theoretical argumentation to offer an applied methodology for the defense of heritage under low-resource conditions.

The wider implication is that of an Integrated Proactive Monitoring System. This would employ the risk map to direct ground patrols of local authorities and community watch groups to areas of high probability, creating a cost-effective, intelligence-based defense network. This system offers a replicable template for application elsewhere in similarly threatened areas of heritage, moving heritage management towards being predictive and preventive, rather than reactive.

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#### 194. "Drivers of Archaeological Looting in the Nile Delta: Leveraging Satellite Remote Sensing and Multilevel Modeling for Spatiotemporal Analysis

*Michelle Fabiani (University of New Haven)*

The scale of archaeological looting internationally, combined with the frequent links to organized crime and geopolitical instability presents an ever-pressing challenge to address. Scholars across diverse fields increasingly recognize the need for proactive approaches to protection that consider looting and trafficking at larger scales. Initial approaches that focused on looting detection using satellite remote sensing (SRS) provided valuable insights into localized patterns of looting and real-time monitoring in conflict (Casana and Panahipour, 2014; Cunliffe et al., 2014). The shift towards refining algorithmic approaches to looting identification, through supervised (Mahmoud et al., 2025; Sech et al., 2024), semi-supervised (Altaweel et al., 2023), and unsupervised approaches (Masini and Lasaponara, 2021) further highlighted the promise of such tools for protection and mitigation. These studies have moved the field forward considerably. Yet, there remains work to be done in both the scale of data collection and identification of drivers and risk factors that predict archaeological looting. These are necessary steps for moving towards proactive, evidence-based policies that can deter and mitigate antiquities looting and trafficking.

Leveraging the availability of SRS data, this study conducts a formal test of drivers of archaeological looting, accounting for both local and regional influences. Specifically, it asks what are the local and regional influences that shape which archaeological sites have looting activity over time in the Nile Delta? To examine this question, very high-resolution (VHR) satellite imagery are systematically, manually, coded to produce an analytically useful dependent variable measure of looting activity in the Nile Delta of Egypt across 140 sites from 2015 to 2017. These are then analyzed in relation to theoretically relevant factors shaping opportunity, drawn from the criminological routine activity theory.

According to this theory, the opportunity for a crime (archaeological looting) is likely to occur when a motivated offender, lack of capable guardianship, and a suitable target co-occur in time and space. Here, this framework is expanded to account for potential nested influences. Site level factors shape individual opportunity structures and target suitability (e.g., prior looting activity, site type, government ownership). Local factors shape accessibility and “capable” guardianship (e.g., proximity to infrastructure, proximity to conflict). Regional factors shape broader trends and affect systematic accessibility and guardianship (e.g., conflict intensity and duration, current and prior unemployment, inflation, drought duration).

To model these factors, this study incorporates diverse data and transforms them to analytically useful and theoretically informed measures. Conflict proximity and intensity are calculated for each month relative to the nearest archaeological site from a composite dataset of terrorism and conflict data (combining the Global Terrorism Database, the Armed Conflict Location and Event Database, and the Uppsala Conflict Data Program). Current and prior unemployment for each governorate are incorporated from Egypt’s national statistics agency (CAPMAS) and a consumer price index is presented from the Food and Agriculture Organization (FAO). Drought duration is measured as the number of consecutive months with drought present, based on NDVI, soil moisture content, and precipitation measures from remotely sensed data provided by the National Oceanic and Atmospheric Agency (NOAA) and the National Aeronautics and Space Agency (NASA). Proximity to local infrastructure (capital cities, populated cities, urban areas, and roads) from the Humanitarian Data Exchange is calculated relative to each archaeological site.

Then, relying on models designed for handling rare events, this study uses a multilevel logit model with nested random effects for the site and governorate to examine drivers of archaeological looting activity (conceptualized as looting attempts) over time. This approach controls for the spatial variation in site location and the differing levels of influence of site, local, and regional characteristics. The influence of a site’s own history of looting (a form of autocorrelation) is accounted for through the inclusion of a separate

prior looting attempts variable. Model fit is assessed through interclass correlations (to assess the validity of the multilevel modelling approach), ROC curves to assess the discriminatory power of the model, and a calibration plot comparing the observed versus predicted probabilities of looting activity.

The results demonstrate that accounting for different levels of influence is important and that net of local and regional factors, site-level characteristics are the most significant and strongest drivers of archaeological looting. Once a site has experienced looting, it’s risk of further damage and degradation increases dramatically. Conflict both increases the baseline risk of subsequent looting up to a spatial threshold; the exact influence varies by type and intensity. Regional factors create a cumulative sense of strain, increasing the baseline risk over time, but has little influence in a given month. Notably, proximity to infrastructure on its own does not have an effect. Combined, these findings suggest that the risk of looting is highly localized, making targeted prevention essential while broader societal influences may provide signals that can be used to allocate resources.

This study faces several limitations that are being addressed through future research. First, due to time and funding constraints, looting activity could only be captured as a binary indicator – in each image was there any evidence of “new” or “prior” looting compared to the previous month? Second, though all available imagery was collected for each site between 2015 and 2017, this represents only 22.91% of all possible site-months in which looting activity could have taken place. As such, these data are a significant underrepresentation of the true scope of possible looting activity. To address this challenge, this study imputed some missing data based on identified patterns in looting activity based on coding of changes in prior looting activity over time. Even so, in cases with significant gaps in coverage, zeros were assumed. Both limitations are significant and statistically increase the chances of a false negative. However, given that the results do find statistical significance, we can be reasonably sure that the relationships presented are meaningful. Finally, while results are only representative of the Nile Delta and cannot immediately be applied to other regions, the method of analysis is

flexible and adaptable to any geographic region, pending data availability. These limitations are currently being addressed in an expanded project that seeks to both algorithmically generate a looting activity measure based on unsupervised algorithmic approaches and to move towards a dynamic risk mapping platform that allows for queries of risk over time and prediction of future risk given specific parameters.

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## 211. Transfer learning with ADAF: extending archaeological detection beyond its training ground

*Nejc Čož (ZRC SAZU)*

*Luka Škerjanec (ZRC SAZU)*

*Žiga Kokalj (ZRC SAZU)*

## Introduction

Automatic Detection of Archaeological Features (ADAF) is a deep learning tool for detecting archaeological features from airborne laser scanning (ALS, lidar) data (Čož et al. 2025). It applies convolutional neural networks (CNNs) for semantic segmentation of ALS derived digital elevation models (DEM) to detect archaeological sites in the landscape. Developed through collaboration between ZRC SAZU, the Discovery Programme (Ireland), Bias Variance Labs, and Transport Infrastructure Ireland, ADAF was designed as a user-friendly application that lowers the technical barrier for archaeologists. Originally trained and validated on Irish and UK ALS data, ADAF's models demonstrated strong performance in recognising barrows, ringforts, and enclosures across Ireland. The present study explores how well a model trained on Irish and UK data performs in a fundamentally different environment, i.e. southern Herzegovina in Bosnia and Herzegovina, and what this reveals about model transferability across contrasting landscapes.

## Methods and Materials

The original ADAF training dataset was built from extensive ALS archives supplied by Transport Infrastructure Ireland. Because of low number of barrows, the dataset was enriched with ALS data from the UK because of morphological similarities of barrows in the two regions. The data were processed using the simple local relief model (SLRM) visualisation, divided into tiles, and paired with manually digitised masks of known archaeological features based on the Sites and Monuments Record. The HRNet architecture was employed for semantic segmentation, implemented through the AiTLAS framework.

To test transferability, the pretrained Irish ADAF model was applied to ALS data from southern Herzegovina, acquired within the ERC project “Unde venis? Unravelling the Enigma of the Stećci Tombstones (STONE, 101089123)”. The project is conducting a comprehensive investigation into the prehistoric and medieval landscape dynamics of the historic region of Herzegovina. In the absence of publicly available ALS data for this area, a dedicated ALS survey was commissioned. The survey covers an area of approximately 3,800 km<sup>2</sup> in eastern Herzegovina, extending from the vicinity of Mostar in the west to the Morine Plateau in the north, the Bileća Basin in the east, and Popovo Polje in the south.

The Herzegovinian landscape, part of the Dinaric karst, contains thousands of prehistoric barrows identified through manual inspection. Prehistoric barrows or burial mounds (locally known as gomile, or humke) are among the most numerous and archaeologically significant archaeological structures in this region, ranging in size from a few meters to up to 30 m in diameter, with both circular and irregular base shapes, they tend to occupy prominent but approachable places in the landscape, low ridge crests, hill spurs above valley floors, and terraces that command long views along river corridors and ancient routeways. In limestone karst zones, barrows are often stone-built cairn mounds set on rocky knolls, while in the more soil rich karst fields they tend to be built from earth. Compared to their Irish and British counterparts, these barrows are smaller, without vegetation cover and densely clustered, while former tend to appear as larger, isolated mounds and covered by grass in gentler terrain. These morphological and environmental differences provide a strong basis for assessing how well an Irish-trained model can generalise to a new archaeological and geomorphological context.

#### Results from preliminary tests

Applying the original ADAF models to the Herzegovinian ALS data produced promising results. The Irish-trained model successfully detected roughly half of the manually recorded barrows, maintaining a notably low false-positive rate. This suggests that, despite environmental and cultural differences, the

morphological signal of barrow-type monuments is sufficiently consistent for partial model transfer.

Performance was lower in areas with dense barrow clusters or pronounced karst microrelief, where the model struggled to distinguish archaeological mounds from natural features such as dolines and rock outcrops. Nonetheless, the quality of the detections exceeded expectations given that no Herzegovinian data were included in the training process. The model’s conservative predictions, yielding few false positives, indicate that it generalises cautiously and relies on robust morphological cues.

#### Discussion

These preliminary results demonstrate both the potential and the limitations of transfer learning in archaeological feature detection. While ADAF’s Irish-trained model recognises many Herzegovinian barrows, differences in scale, spacing, and landscape texture reduce recall. Such limitations highlight the availability (or rather lack) of training data as a key challenge in deep learning for archaeology, especially for generalisation across different domains.

The next phase will involve retraining ADAF with a curated Herzegovinian dataset derived from the ERC STONE ALS data. By fine-tuning the original model with expertly labelled examples from Herzegovina, we aim to quantify improvements in detection accuracy and better understand how model adaptation can enhance the results. The study will also analyse which features of the Herzegovinian dataset (e.g. morphology, slope, elevation, or context) most affect transfer performance.

Beyond technical refinement, this research contributes to broader discussions on AI transferability in archaeological prospection. Developing adaptable models across regions is essential for scaling up automated detection methods beyond local datasets. By systematically evaluating performance in distinct geomorphological settings, we aim to outline best practices for reusing pretrained archaeological models and sharing training data between projects.

#### Conclusion



Testing ADAF in southern Herzegovina demonstrates that deep learning models trained on one region can successfully identify similar archaeological features in another, even across substantial environmental contrasts. The results underscore both the robustness of CNN-based detection and the necessity of region-specific retraining.

Future work within ERC STONE will refine ADAF through domain adaptation, creating a model tailored to the karstic environment. This will provide valuable insights into the scalability of archaeological AI and its potential for cross-regional applications. Ultimately, this study contributes to developing a reproducible, transferable framework for automated archaeological detection, integrating deep learning, ALS data analysis, and landscape archaeology within complex terrains.

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## 286. Introducing AI Chatbots for Remote Sensing Archaeology

*Nicolas Melillos (Cyprus University of Technology)*

Conversational artificial intelligence and remote sensing are converging into a promising new field for digital archaeology. While multimodal chatbots and large vision–language models are already reshaping geospatial analysis and environmental monitoring, archaeological applications remain almost entirely limited to text-based interaction. Building upon the findings of the recent study, this presentation will introduce the first implementation phase of an ongoing PhD project that aims to design, develop and evaluate a domain-sensitive multimodal chatbot prototype to assist in the interpretation and image extraction of archaeological remote-sensing data and archaeological proxies. The design integrates natural-language dialogue with preliminary image-analysis capabilities, allowing users to explore satellite, and drone imagery through intuitive conversational queries. Preliminary results, to be presented at CAA 2026, highlight how such interaction can reduce technical barriers, promote accessibility, and support interpretative reasoning between humans and AI systems. Beyond demonstrating the technical concept, the work aims to open a discussion on how conversational AI can be responsibly embedded within archaeological research workflows, contributing to a more inclusive and collaborative digital archaeology.

## 296. Popularising archaeological predictive modelling: An application on neolithic settlements in Thrace

*Ilias Ladenis (International Hellenic University)*

*Kyriakos Sgouropoulos (Democritus University of Thrace)*

*Dushka Urem-Kotsou (Democritus University of Thrace)*

Archaeological predictive modelling beyond cultural resource management applications, is also a useful tool for archaeological research, since it can assist in accelerating and adopting a more targeted approach to wide field survey projects, as well as in tracing habitational patterns (Verhagen and Whitley 2020). The latter is especially valuable for research of the Neolithic period, since the only evidence of settlements and human mobility comes from archaeological data and not written sources, making these analyses valuable for interpreting the variables that permitted habitation (Wu, et al. 2023).

In attempting to apply predictive spatial analysis to determine possible site locations in Thrace, an issue arose, as the archaeologists are not expected to have coding knowledge or familiarity with machine learning modelling. This results in a considerable learning curve in spatial analysis and machine learning, as well as in model coding. These limitations are usually enough to discourage an archaeologist from attempting to engage in such analyses. This issue, although not seen as a problem, but a challenge, to investigate how the average archaeologist can train such models and decide what the optimal variables are to be used and given the data size that is available at each instance. The goal was to construct a feasible, simple, and easily reproducible methodology based on the traditional predictive modelling methodology, but in a simple way so that this analysis can be routinely performed by any archaeologist on any custom data that may be available.

In order to achieve this goal, a few workflow pillars were established. Only published data were used, and free-to-use software was utilised both in terms of coding and GIS. The main body of data comes from 100 Neolithic sites from across Thrace, which were investigated by archaeological and geophysical surveys or excavations. Additional spatial data were derived from

the EU Digital Elevation model (DEM) and the Copernicus Land Monitoring Service. The collection of data was followed by the use of AI for coding purposes, making the process faster and much more accessible to average archaeologist (Ross, et al. 2023), demystifying an analysis and transforming it into a powerful tool to be widely used in research.

The general workflow was divided into stages. Initially, the data had to be prepared in such a way as to achieve complete interchangeability for testing various modelling techniques and comparing results and effectiveness. The second part is the model training and the evaluation. In more detail in the second part, a loop between the archaeologist and the AI is implemented in order to create and refine the code. By looping the information with the AI, the user is provided with the ability to tweak the code by inputting instructions which are based on archaeological knowledge, thus training the AI in the process and also training themselves in the specialized terminology of machine learning and coding, and understanding specifics on how these analysis work in practice.

In the end, a workflow pipeline was established based on this closed loop of input and correction, along with proper data preparation. This was followed by testing and evaluating three predictive modelling techniques (Maximum Entropy, Logistic Regression and Random Forest) on their ability to train and adapt to this dataset from various perspectives regarding data imbalances and environmental variables, in order to establish peak performance. Concerning the modelling techniques' performances after successfully creating robust code, evaluating and testing using the described workflow, a 1 to 10 analogy of real site data and background random data, it was found that Maximum Entropy (AUC 0.8) gave the highest score on discriminating between real testing sites and background data, closely followed by Logistic Regression (AUC 0.75), while Random Forest was not adapting in the same way (AUC 0.66), presenting results slightly better than pure randomness. These are quite encouraging results that can be refined even more, proving that at least 2 models can be used to determine possible areas of high probability for the location of neolithic settlements in Thrace to assist in the search for sites that are yet to be discovered.

The aforementioned process was repetitive, but it successfully led to a cleaner, simpler and reproducible workflow pipeline revealing several key findings. Importantly, the direct involvement of the archaeologist in the coding procedure, facilitated by AI and data preparation, allowed archaeological questions and input to directly affect the coding procedure and the model's variables. This enabled flexibility through interchangeability between models and robustness in the workflow. This workflow elevates the accessibility of such analyses, proving that through iterative AI assistance and data preparation for interchangeability, it can be used by anyone. Potentially, it could be implemented in a wider variety of spatial and statistical archaeological analyses in the same way.

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### 357. Can we detect ancient canals with AI: Leveraging big multitemporal multisource satellite data and deep learning to detect complex and invisible landscape features

*Nazarij Bulawka (University of Warsaw)*

*Hector Orengo (Barcelona Supercomputing Center)*

*Felipe Lumbreras Ruiz (Universidad Autónoma de Barcelona)*

*Iban Berganzo-Besga (Barcelona Supercomputing Center)*

*Ekta Gupta (Landscape Archaeology Research Group (GIAP), Catalan Institute of Classical Archaeology)*

The study of water management systems is a key area of research into ancient Mesopotamian civilisation (Rost 2022). It involves reconstructing ancient watercourses and canals preserved as raised embankments (levees). This extremely time-consuming task requires multiple methods, ranging from historical analysis to geographic information systems (GIS). With the advent of artificial intelligence, one solution discussed is automation, but this is not without challenges.

This study presents a deep learning-based approach to the large-scale, semi-automated detection of ancient levees in central Iraq. This approach integrates big multitemporal and multisource satellite datasets with advanced instance segmentation models.

The study is based on the incorporation of large, publicly available remote sensing datasets in Google Earth Engine, together with the TanDEM-X Edited Digital Surface Model (DSM). The workflow was also tested using the Copernicus GLO 30 dataset. Several datasets were created from multitemporal Landsat 5, Sentinel-1 SAR and Sentinel-2 multispectral imagery, along with the TanDEM-X Edited DSM, and results of their processing, including vegetation and moisture indices, PCA reductions of seasonal variability and the

Multi-Scale Relief Model (MSRM). Training labels were generated through threshold-based automatic extraction and detailed manual digitisation of levees between Al Hillah and Ar Rymaythah in Iraq. Three architectures — U-Net, Attention U-Net and Swin UNETR — were evaluated on datasets containing 53, 48 and 36 bands, respectively.

Results demonstrate that Swin UNETR consistently outperformed other models, particularly when trained on the 48-band dataset. The study indicates that wide automatic annotations, which gave better metrics (precision of 0.7484, recall of 0.8259), but produced irregular, noisy patches. At the same time, thin manual annotations yielded clearer, more linear predictions, which were later refined with post-processing (precision of 0.5140 and a recall of 0.5919). Metric scores of the most recent model are related to levee irregularity, which is difficult to address using manual digitisation during training and test datasets. The model allowed for the prediction of levee networks across a large area, extending from Babylon to Uruk. A comparative analysis with independent palaeochannel reconstructions (Jotheri 2016) confirmed that the model identified many of the most prominent irrigation features and can eliminate misclassifications in urban areas. Our study highlights that automated predictions cannot yet replace interpretative digitisation, but they provide reproducible, standardised, and scalable outputs that can accelerate archaeological mapping and support regional-scale analysis.

The paper will present the methods and results of recently developed deep learning model for levee detection, present successes, challenges and pitfalls of applied methodology, and discuss future plans.

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## 370. Monitoring submerged cultural heritage: AI-driven detection of suspicious vessel activity over underwater archaeological sites using optical satellite images

*Maria Cristina Salvi (Eratosthenes Centre of Excellence)*

*Dante Abate (Eratosthenes Centre of Excellence)*

*Iban Berganzo-Besga (Barcelona Supercomputing Center)*

*Hector A. Orengo (Barcelona Supercomputing Center)*

### Introduction

Illicit underwater excavations pose a persistent and growing threat to submerged cultural heritage (UNESCO 2001), particularly in regions where ancient shipwrecks and underwater settlements overlap with contemporary maritime activities. Unlike terrestrial looting, where ground disturbance leaves visually detectable signs, underwater looting often occurs covertly, facilitated by the mobility of small private vessels that can approach archaeological sites with minimal observation. Traditional monitoring frameworks rely heavily on on-site inspection, diver patrols, or enforcement collaboration with coast guards, measures that remain resource-intensive and frequently reactive. Recent advancements in high-resolution satellite imagery, increased revisiting time and artificial intelligence (AI) provide new opportunities to detect early indicators of illegal underwater activities by monitoring patterns of vessel presence and behaviour.

This paper presents the development and preliminary testing of an AI-driven system for the automatic detection and tracking of small vessels loitering above known underwater archaeological sites, using high- and medium-resolution optical satellite imagery as its primary data source.

The core research questions addressed are:

1. Can high-resolution satellite imagery be reliably used to detect small and mid-sized vessels in maritime areas where submerged heritage is present?

2. Can vessel-related spatial and temporal behaviour be modelled to distinguish normal maritime traffic from patterns indicative of potential looting activity?
3. Which AI architectures and dataset construction strategies prove most effective for this type of monitoring?
4. Are super-resolution techniques applicable for upscaling medium-resolution imagery for underwater heritage protection?

#### Methods and Materials

The research adopts a workflow designed to automatically detect vessels in high- and medium-resolution satellite imagery and to analyze their behaviour in relation to known underwater archaeological sites which are difficult to patrol on regular basis. The methodology involves the construction of a dedicated image dataset, the annotation of target features, the application of data augmentation techniques to improve model robustness, and the selection and training of an object detection architecture.

#### Data sources

Primary imagery was obtained from Planet SkySat, which provides 50 cm pixel size spatial resolution suitable for the identification of small and mid-sized vessels. A time-series collection was compiled for coastal regions and offshore underwater archaeological sites in Cyprus: the dataset includes images captured under varying environmental conditions, including differences in sea state, illumination, seasonal factors, and viewing geometry, enabling the model to generalize across realistic maritime observation scenarios.

#### Dataset construction

While several open-source datasets exist for general vessel detection in satellite imagery (Patel, Bhatt, and Mazzeo 2022; Matasci et al. 2021), these primarily focus on large ships in open-water commercial or industrial maritime contexts. However, no publicly available dataset currently addresses the detection of small and medium-sized vessels. For this reason, a dedicated

dataset was constructed to reflect the spatial, contextual, and behavioural conditions relevant to underwater cultural heritage protection.

Each SkySat acquisition was subdivided into smaller spatial patches to increase sample quantity and to isolate vessel targets within different maritime settings, such as open water, coastal anchorages, bays, and near-shore transit zones. This systematic cropping approach enabled the representation of a wide range of vessel sizes, orientations, and wake patterns, improving model capacity to recognize objects across diverse appearances.

#### Annotation

Manual annotation was carried out using standard bounding box labelling tools. A single class (“vessel”) was defined for the initial detection stage, with the understanding that behavioural assessment, distinguishing routine maritime activity from potentially suspicious loitering, would be derived from multi-temporal analysis rather than classification during training.

#### Data augmentation

To increase dataset diversity and improve the model’s ability to handle environmental variability, augmentation techniques were applied, including geometric transformations, radiometric adjustments, and controlled noise models simulating surface glint and atmospheric conditions. These augmentations enhanced resilience to environmental distortions inherent to satellite-based maritime imaging.

#### Model architecture and training

An advanced deep-learning object detection framework was applied to identify vessels in high-resolution satellite imagery. Multiple model configurations were compared to optimize the balance between accuracy and processing efficiency. Data were divided into training, validation, and test sets, and training parameters were refined iteratively to improve detection confidence and bounding box accuracy.

#### Temporal Analysis

Vessel detections were compared across multi-date imagery using spatial clustering to identify repeated presence within the same local area.

## Results

Preliminary tests showed promising detection performance demonstrating high recall for vessels >5 meters in length and moderate recall for very small personal watercraft (<3 m).

While the initial detection results demonstrate that vessels can be reliably identified in single-scene acquisitions, continuous behavioural analysis remains dependent on image revisit frequency. The used imagery provides high spatial resolution but limited temporal coverage, which constrains the system's ability to confirm repeated presence or prolonged stationary behaviour, both key indicators of potential looting risk. The workflow, however, is fully compatible with higher-frequency imagery: if daily or near-daily acquisitions were available, the same detection and spatial clustering pipeline could be applied to identify recurrent vessel presence and generate early-warning alerts, rather than solely documenting single events.

## Discussion

The development of a vessel monitoring AI system for underwater cultural heritage protection highlights the potential of satellite-based surveillance to augment limited in-field enforcement capabilities. Key implications include:

- Operational scalability. Unlike aerial or diver inspection patrols, satellite-based monitoring can cover extensive maritime areas with regular revisit rates.
- Early detection and rapid response. The ability to identify loitering patterns in near real-time can enable preventive intervention rather than reactive documentation of damage.
- Interdisciplinary integration. Effective deployment requires collaboration between archaeologists, satellite data analysts, marine monitoring agencies, and law enforcement.
- Limitation. The approach is dependent on high-resolution imagery availability and is challenged by cloud cover, sea state variability, and false

positives associated with legitimate recreational anchoring. Another limitation is the temporal coverage of the data. Daily image availability is necessary to monitor repeated vessel, important indicator of potentially suspicious activity. Ongoing refinement involves integrating Automatic Identification System signals and regional maritime traffic data to disambiguate routine versus suspicious presence.

The results of this study indicate that high-resolution satellite imagery combined with deep-learning object detection can support the systematic identification of vessels operating near submerged archaeological sites. The approach provides a scalable foundation that could evolve into an early-warning capability as higher-frequency imagery becomes available.

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## S10: Exploring Past Senses. Digital Tools and Methodologies for Sensory Archaeology

*Kamil Kopij, Institute of Archaeology, Jagiellonian University*

*Alexander Braun, University of Cologne*

**Location:** Franz König Saal

**Session Format:** Standard

How past humans experienced their environment is one of the greatest challenges in archaeology. Audible, visual, and olfactory stimuli shaped human perceptions, experience, memory, responses. These stimuli were, in turn, influenced by human actions across diverse social contexts.

In recent years, computational methodologies have proven that it is possible – within reasonable limits – to model aspects of human sensory experience. With the growing availability of digital tools, archaeologists are increasingly exploring how past humans experienced their environment and how they shaped it in response and in regard to sensory stimuli.

Advances in digital tools provide exciting new prospects for analysing these experiences, their functions, and their interactions with individuals. These advancements foster the development of new synergies and methodologies, allowing for more comprehensive investigations.

This session invites discussion of both established and emerging tools and methodologies to approach the questions of sensory archaeology: what did people experience in the past – and how? What information can we glean with our approaches on a theoretical and empirical level about past humans and their societies? But also, what are the limitations, and biases introduced by our data and methods?

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**14:00 – 14:20** 15. A Comparative Approach Between In-Field and Computer-Generated Sound Modeling in an Ancient Maya Cave Site  
*Graham Goodwin (U.C. Merced); Holly Moyes (U.C. Merced)*

**14:20 – 14:40** 17. “Putting the Body in its Rightful Place”: Assessing Bodily Senses in Late Cypriot Mortuary Rituals at Alassa Pano Mantilaris  
*Dimitris Gavril (National and Kapodistrian University of Athens)*

**14:40 – 15:00** 30. Exploring Changes in Symbolic Expression through Eye-Tracking: A Comparative Case Study of Prehistoric Pottery in Northern Europe and Central Germany  
*Lizzie Scholtus (Christian Albrecht Universität zu Kiel); Bruno Vindrola-Adrós (Christian Albrecht Universität zu Kiel)*

**15:00 – 15:20** 62. Cocktail Party at the Forum Romanum: Acoustics, Visibility, and the Sensory Politics of Roman Oratory  
*Kamil Kopij (Jagiellonian University); Adam Pilch (AGH-University of Krakow); Szymon Popławski (Independent); Monika Drab (Wrocław University of Science and Technology); Kaja Głomb (Jagiellonian University)*

**15:20 – 15:40** 95. Sensing the Sacred: Exploring the Potential of Virtual Reality in Sensory Archaeology  
*Johanna Roiha (Finnish Geospatial Research Institute FGI); Marja Ahola (University of Helsinki); Juha Oksanen (Finnish Geospatial Research Institute FGI)*

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| <b>15:40 – 16:00</b> | 108. The Archaeology of the Senses in an Ancient Egyptian House: Reconstructing a Cognitive Map through Visibility and Movement Analysis<br><i>ŁUKASZ JARMUŻEK (University of Warsaw)</i>                                              |
| <b>16:00 – 16:30</b> | Coffee break                                                                                                                                                                                                                           |
| <b>16:30 – 16:50</b> | 131. Senses and Spaces: Multimodal Investigations into Ancient Lived Experiences<br><i>Laura Nissin (University of Helsinki); Ella Peltonen*; Benjamin Kämä*; Mikko Mäkitalo*; Alekski Vuorinen*</i><br><br><i>*University of Oulu</i> |
| <b>16:50 – 17:10</b> | 188. Archaeology of the Intangible through Movement and Touch<br><i>Willeke Wendrich (Polytechnic University Turin)</i>                                                                                                                |
| <b>17:10 – 17:30</b> | 196. From Visibility to Perceptibility: A Deep Learning Framework for Horizon Profile Analysis at the Jin Dynasty Ritual Site of Baomacheng<br><i>Zehao Li (University College London)</i>                                             |
| <b>17:30 – 17:50</b> | 209. Visual Communication on ancient public squares: 3D vector visibility analysis and large<br><i>Alexander Braun (University of Cologne)</i>                                                                                         |
| <b>17:50 – 18:10</b> | 458. Exploring Medieval Sacred Soundscapes: Digital Tools and Methods for the Archaeology of Sound, Hearing, and Listening<br><i>Zorana Đorđević (University of Barcelona)</i>                                                         |
| <b>18:10 – 18:30</b> | Discussion                                                                                                                                                                                                                             |

## 15. A Comparative Approach Between In-Field and Computer-Generated Sound Modeling in an Ancient Maya Cave Site

*Graham Goodwin (U.C. Merced)*

*Holly Moyes (U.C. Merced)*

Archaeoacoustics investigates how sound interacted with the built and natural environments of past societies (Scarre and Lawson 2006). In-field methods have long been the primary approach to quantifying acoustic parameters at archaeological sites (Mattioli and Diaz-Andreu 2017). However, in-field methods often face logistical challenges including environmental hazards, fragile site preservation, and limited sampling opportunities. Advances in 3D scanning and virtual acoustics software have opened the possibility of evaluating site acoustics through computer-generated models (Goodwin 2024). This study compares in-field measurements with computer based simulations for the entrance chamber of Las Cuevas, an Ancient Maya cave site in Belize, to assess the reliability of simulation as an alternative or complement to traditional in-field methods.

### Methods and Materials

In-field acoustic testing of the entrance chamber was performed in 2017 by Margarita Díaz-Andreu and Tommaso Mattioli using impulse-response (IR) techniques. A balloon burst at a height of 1.7 m served as the sound source, and an omnidirectional microphone with a digital recorder captured the responses at 15 locations. Acoustic parameters of interest included C50 (clarity of speech) and T(20) (reverberation time derived from the decay of 60 dB).

For comparison, a detailed 3D model of the chamber was generated in 2022 using a SLAM-based Hovermap LiDAR unit during the Las Cuevas Archaeological Reconnaissance (LCAR) field season. A portion of this model from Las Cuevas entrance chamber was then cleaned, meshed, and optimized for

import into the Odeon acoustic software. The Odeon simulation used two historically plausible sound-source locations—a raised “oration station” platform and the elevated “window” overlooking the chamber—both modeled as an 80 dB male speaking voice. Receiver points mirrored the 15 in-field sample locations.

To enable cross-comparison of the two datasets, C50 values from the field and STI (Speech Transmission Index) values from Odeon were normalized to a common 0–1 scale using min-max rescaling, allowing statistical analysis of speech intelligibility. Two-tailed paired t-tests were performed on T(20) values at each receiver across octave bands (63–4000 Hz).

### Results

Paired t-tests comparing Odeon and in-field T(20) values found no statistically significant differences at any receiver except one anomalous location (P16). Mid-frequency reverberation times of ~2.0 s across methods align with acoustic targets for modern concert halls and suggest favorable conditions for speech and music.

Histogram analysis of rescaled C50 and STI distributions revealed similar positively skewed patterns, indicating that despite differences in scale and metric, both methods converged on comparable spatial acoustic patterns.

### Discussion

The close agreement between simulated and measured data demonstrates that virtual acoustic modeling in Odeon is appropriate for archaeoacoustic analysis in a complex setting such as Las Cuevas. These findings imply that, once validated by limited field testing, simulations can serve as a reliable, minimally invasive, and cost-effective alternative—particularly valuable for sensitive or logistically challenging sites where extensive equipment placement is impractical or potentially damaging.

While Odeon cannot capture all aspects of the lived soundscape such as background water flow, or exact surface details. The tool nevertheless proved robust enough to replicate acoustic parameters relevant to

archaeological interpretation. This supports the use of computer modeling for preliminary assessments, and even stand-alone analyses.

Future work should expand to additional Maya cave sites. A wider dataset could clarify whether the favorable reverberation and intelligibility patterns at Las Cuevas were incidental or deliberately sought by ancient people selecting ritual performance spaces.

By demonstrating that sound within the entrance chamber achieves ideal reverberation and clarity in both real-world and computer analysis, this study underscores the likelihood that auditory experience was integral to the ceremonial function of Las Cuevas. Ultimately, such approaches can illuminate how past communities perceive their acoustic environments.

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## 17. “Putting the Body in its Rightful Place”: Assessing Bodily Senses in Late Cypriot Mortuary Rituals at Alassa Pano Mantilaris

*Dimitris Gavriil (National and Kapodistrian University of Athens)*

During the transition from the Middle to Late Bronze Age (1750/1700–1550 B.C.), Cypriot societies underwent radical organizational transformations. One striking change was the relocation of burial zones from areas outside urban layouts into public spaces close to active residential units. This shift is often been interpreted, as a symbolical attempt to reassert mourners’ rights over ancestral heritage and property (Keswani 2004). However, symbolic readings alone do not explain the material implications of this practice for the organization and reproduction of urban social life.

Given that the archaeological discipline has integrated excavation techniques with a primary emphasis on establishing spatio-temporal sequences of the human past, research can assess behavioral outputs and material conditions that gave rise to specific, yet variable and changing, lifeways (Barrett 2021). The latter were being shaped by the interactions of human and non-human agents, which led to different social experiences on a case-by-case basis. Because the body is a central constituent of our humanness and our ability to contemplate the world, it is set in the epicenter of this approach along with two other interlocking agents, namely things and spaces. The interplay of material configurations and qualities among bodies, things, and spaces conditioned their synergy and the social experiences that emerged from it.

This theoretical framework underpins the use of 3D modelling to reconstruct and analyze these interactions. The present study focuses on how both secular and mortuary spaces structured mortuary rituals at Alassa Pano Mantilaris, which are challenging to fully visualize without digital reconstruction. The digitalization and experiential re-engagement through interactive visualization provide an opportunity to assess bodily movements and spatial features of mortuary monuments that are neglected or no longer accessible

(Artopoulos 2017). Bodily dimensions from osteoarchaeological reports are incorporated to examine the practical use of tombs, while spatial features (e.g., rock type, dimensions, shapes) are reconstructed from recorded archaeological data. Preliminary analysis indicates that the limited interiors of the tombs were unsuitable for social gatherings, which likely took place in peri-sepulchral zones such as streets. These areas, serving as conduits of circulation, points of access to private units, and venues for processions and feasting, reveal the versatile role of streets in structuring social and mortuary practices and highlight a communal need for spatial reproduction.

Beyond offering a state-of-the-art means of reconstructing ancient lifeways, interactive visualization serves as a valuable tool for analyzing and reappraising past practices and lost monuments. It is important to recognize, however, that interactive visualization rely on data already procured and interpreted by archaeological expeditions. The biases inherent in excavation and interpretation are therefore embedded in the process. Yet, rather than being more biased than traditional interpretive frameworks, interactive visualization can actually reduce the risk of inhabiting the past in purely imaginative or speculative ways by grounding reconstructions in visualizations of material evidence.

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### 30. Exploring Changes in Symbolic Expression through Eye-Tracking: A Comparative Case Study of Prehistoric Pottery in Northern Europe and Central Germany

*Lizzie Scholtus (Christian Albrecht Universität zu Kiel)*

*Bruno Vindrola-Adrós (Christian Albrecht Universität zu Kiel)*

Understanding the interplay between material culture and cognitive processing is a central concern in sensory archaeology (Vindrola-Adrós et al., 2025). Symbolic expression can be seen through material culture designs and in turn these designs structure attention through visual engagement. The XSCAPE-Material Minds project investigates how material culture actively shapes patterns of attention (Criado-Boado et al., 2023). Within this framework, we study how shifts in prehistoric pottery styles correspond to transformations in social and symbolic practices in Northern Jutland (Denmark) and Central Germany over five millennia (5500–1 BCE). By combining archaeology, cognitive science, and experimental methodologies, we aim to quantify how different ceramic styles influence attention.

Two complementary eye-tracking experiments were conducted in controlled settings, one in northern Jutland and one in central Germany. Participants observed representative prehistoric pottery from each region under standardised conditions. Eye movements were recorded in real time, capturing fixation positions and durations to assess patterns of attention and visual processing demands. Heatmaps and temporal analyses of fixations allowed identification of which decorative elements attracted attention and how this varied across chronological phases. Data were aligned with the respective chronological frameworks of each region, permitting diachronic and comparative analyses.

The results indicate that fixations were predominantly directed towards decorative patterns rather than vessel shapes, with systematic variations over time. From approximately 3500 BCE, both regions show synchronous increases in attention to decoration, coinciding with the expansion of supra-

regional ceramic networks. This synchrony is interpreted as reflecting inter-regional contacts facilitated by exchange networks. In later periods, attention towards pottery decoration declines as metal objects increasingly assume symbolic and economic significance. Sharp differences in visual responses to the earliest pottery styles, e.g. Ertebølle pottery in Jutland and Linearbandkeramik in central Germany, illustrate regional differences in the symbolic investment in material culture.

Eye-tracking offers a quantitative approach to examine how changes in material culture affect attention and cognitive engagement. Variation in ceramic design appears closely linked to broader socio-historical processes, including the emergence of large exchange networks, shifts in craft specialisation, and media displacement towards metal objects. This methodology allows the exploration of symbolic and cognitive dimensions of material culture without claiming to reconstruct past perceptual experience, and provides new perspectives on the reciprocal influence between material culture, attention, and broader socio-historical transformations.

Criado-Boado F, Martínez LM, Blanco MJ, Alonso-Pablos D, Porto Y and Barrio-Álvarez E del (2023) Gazed Pottery: an Archaeometric-Cognitive Approach to Material Culture Visuality. *Journal of Archaeological Science* 154: 105770.

Vindrola-Adrós B, Scholtus L, Furholt K and Müller J (2025) A guide to the mechanisms of transformation: The role of materials in cognitive change. *Archaeological Dialogues*: 1–24.

## 62. Cocktail Party at the Forum Romanum: Acoustics, Visibility, and the Sensory Politics of Roman Oratory

*Kamil Kopij (Jagiellonian University)*

*Adam Pilch (AGH-University of Krakow)*

*Szymon Popławski (Independent)*

*Monika Drab (Wrocław University of Science and Technology)*

*Kaja Głomb (Jagiellonian University)*

### Introduction

This paper investigates Roman public speaking as a ritualised form of civic performance embedded in the monumental setting of the Forum Romanum. In this environment, the body and voice of the orator functioned as key instruments for enacting authority, persuasion, and collective identity. Focusing on the late Republican and Early Imperial periods, the study asks how the architecture and spatial organisation of the Forum shaped the sensory experience of public address and conditioned the participation of ancient audiences.

### Methods and materials

We conceptualise the Forum as an oratorical taskscape—a dynamic space structured by the interaction of sound, movement, and architecture. To analyse this relationship, we employ digital methods integrating acoustic simulation and visibility analysis. 3D reconstructions of major speaking platforms (rostra vetera, rostra aedis Castoris, rostra Augusti, rostra aedis divi Iulii) were used to model the propagation of sound under different background noise levels and to determine how gestures, posture, and facial expressions would have been visible from different parts of the Forum. The two datasets were then combined through spatial overlays and perceptual modelling, taking into account psychoacoustic phenomena such as the “cocktail party effect.”

### Results

The integrated model identifies zones within the Forum where audiences could both hear and see the orator clearly, thus participating most fully in the performance. The size and distribution of this effective audience varied with the location of the speaker and the surrounding architectural features, showing that the built environment directly influenced the reach and impact of oratory.

### Discussion

By merging acoustic and visual analyses, the study demonstrates that Roman public speaking operated as a multimodal and embodied practice, dependent on the sensory affordances of space. The Forum emerges as an active participant in the communicative process—a ritual landscape where architecture, movement, and sound co-produced civic meaning and political authority.

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## 95. Sensing the Sacred: Exploring the Potential of Virtual Reality in Sensory Archaeology

*Johanna Roiha (Finnish Geospatial Research Institute FGI)*

*Marja Ahola (University of Helsinki)*

*Juha Oksanen (Finnish Geospatial Research Institute FGI)*

### Introduction

How did people in the past experience their surroundings – not just visually, but through all their senses? What was the role of this multisensorial experience of place and landscape to ritualized actions? Forests, as dynamic and multisensory environments, provide a particularly rich context for exploring such experiences. In Finland and the broader boreal region, forest landscapes have long been associated with spirituality, sacredness, and ritualized practices. Yet, the embodied experience of being in a sacred place locating in a forest is hard to grasp. What makes this place special? Why was it chosen for these actions?

In recent decades, researchers have studied such sites using a phenomenological approach that emphasizes being in a place and having an embodied experience of the landscape rather than relying on two-dimensional maps and documentation. This suggests that landscapes played a pivotal role in past religions and ritualized actions. However, such multisensory analyses of landscapes often privilege the personal experiences of researchers over the diverse and socially mediated experiences of people in the past, raising questions about subjectivity (Brück 2015)

This paper discusses the potential of virtual reality (VR) as a methodological and reflective tool for exploring sensory aspects of past landscapes (cf. Falconer et al. 2020). Working in the context of the Sacred Forests Around Us -project, which investigates long-term relationships between people and forests, we consider how immersive VR environments might help us to

approach questions of place, perception, and sacredness more objectively. Instead of presenting finished results, this contribution reflects on the methodological potential and constraints of VR in relation to sensory archaeology and the “sense of place.”

### Materials and methods

Our approach integrates archaeological and folkloric data with geospatial and ecological modelling. Using digital elevation models (DEM), we will reconstruct prehistoric forest landscapes at selected sites that contain material remains or oral traditions associated with past ritualized activities in hinterland settings. To achieve this, we will document the sites through drawings, photographs, videos, and field notes that pay close attention to factors such as changing light conditions and how the landscape enables or constrains particular ways of being, moving, or acting (e.g. Ahola et al. 2024).

These simulations, all based on fully automated processes making use of open-source tools, are being developed for immersive VR presentation using Varjo XR-4 headsets, providing an experimental framework for exploring the influence of sensory parameters such as light, vegetation density, and sound to the “sense of place”.

To gain a holistic understanding of embodied experiences of place and landscape – and thereby to explore why certain sites were chosen for ritualized activity – we will present these models in virtual environments and invite participants to “visit” the reconstructed prehistoric forests. This is important, as VR offers a pathway toward accessibility and participation. Unlike physical fieldwork, virtual experiences can be shared widely, allowing researchers, students, and the public to engage with places that are remote, fragile, or seasonally inaccessible (Brück 2015).

After exploring the VR models, participants will participate to semi-structured in-person interviews about their experiences within the virtual environments. Their reflections will be compared with our documented observations from the corresponding physical sites, enabling a direct dialogue between embodied, real-world encounters and digitally mediated ones. This

approach offers a way to study how sensory perception, feelings of sacredness, and environmental context interact and influence each other.

#### Discussion

At present, we are collecting archaeological and oral data on past sites of ritual activity and developing preliminary VR forest models to test the technical workflow for immersive landscape reconstruction. In the coming months, we will identify the most suitable sites and undertake detailed field documentation. Throughout these phases, we approach VR as a methodological experiment – a means of thinking with and through technology. The experience of virtually “being” within a reconstructed forest serves as a heuristic tool, inviting reflection on perception, embodiment, and cultural imagination. What constitutes the “feel” of a place? To what extent is that experience visual, auditory, or contextual? And how might our own modern sensory expectations shape the ways we reconstruct and interpret these past environments?

What makes VR particularly intriguing for sensory archaeology is its potential to manipulate environmental conditions - something rarely possible in real-world fieldwork. Within a virtual landscape, it will eventually be possible to alter, for example, light, season, vegetation density, and ambient soundscapes to examine their influence on perception and emotion. This is important, because e.g. the role of light has proven to be important to past ritualized activities. In contrast, present-day environments are often shaped by factors such as noise pollution, artificial light, or restricted accessibility that limit our ability to experience landscapes in their historical or preindustrial form. While VR cannot yet reproduce elements such as smell, wind, or the tactile sensation of soil underfoot, it provides a space where certain sensory dimensions—light, sound, and spatial immersion – can be examined under controlled and repeatable conditions. Thus, the virtual environment becomes both a complement and a counterpoint to the lived experience gathered through fieldwork. Ultimately, the use of VR in this context is less about achieving realism and more about exploring possibilities of experience – to

ask what it means to sense the past and how digital tools might help us approach that question.

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## 108. The Archaeology of the Senses in an Ancient Egyptian House: Reconstructing a Cognitive Map through Visibility and Movement Analysis

ŁUKASZ JARMUŻEK (*University of Warsaw*)

**Keywords:** archaeology of the senses, cognitive map, movement analysis, visibility analysis, settlement archaeology of Pharaonic Egypt, DepthmapX

This paper aims to present a research method that allows for a more detailed examination of residential architecture, using ancient Egyptian houses as a case study. Traditional analysis techniques, which rely on typologies derived from floor plans, have notable limitations. These typologies (Tietze 1985) usually assume an idealised arrangement of rooms that rarely matches

actual constructions. Even when such layouts exist, the fact that mudbrick houses could be easily modified often led to significant structural changes over time—an aspect usually overlooked in standard studies. Additionally, there is the issue of dividing houses into public, private, and intermediary zones arbitrarily. The inconsistent criteria used often result in categorising very different houses as tripartite (Correas-Amador 2013).

Therefore, a new research approach is needed, incorporating methods that provide more precise descriptions of how domestic spaces change and are used. These methods should prioritise the perspective of house occupants rather than solely focusing on the researcher analysing architectural plans. In this context, applying the principles of the archaeology of the senses—which explores how space influences inhabitants' senses—is valuable. As people move through a house, they form a cognitive map based on sensory input and cultural knowledge, which helps them understand the function, meaning, and symbolism of each room. While we cannot fully comprehend how ancient Egyptians experienced their homes, modern digital tools enable us to develop models that bring us closer to that understanding.

This paper introduces a method that employs visibility and movement analysis to reconstruct a cognitive map of space. The technique is rooted in spatial analysis, known as space syntax, which was developed by Bill Hillier and Julienne Hanson at University College London during the 1980s. The introduction of DepthmapX software in the early 21st century has significantly expanded this method's analytical capabilities. Visibility and movement analysis support various types of building studies, including one by John Peponis (2012), which conceptualises space through what he terms "a visual turn".

His method was used to analyse over 120 buildings spanning three historical periods of ancient Egypt: the Old, Middle, and New Kingdoms. The analysis showed that house structures evolved over time: Old Kingdom buildings had the most intricate layouts, making spatial understanding more difficult, whereas in later periods, layouts became progressively simpler. These shifts may reflect changes in the concept of privacy or a decline in the use of productive spaces within homes. The research also identified structures likely serving more public functions, which is noteworthy because purely public

buildings were uncommon in ancient Egyptian architecture, unlike in other cultures. Additionally, the presentation will demonstrate how visibility analyses can enhance understanding of the spatial organisation of larger complexes, such as royal palaces or domestic estates that include houses, store-rooms, and workshops.

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### 131. Senses and Spaces: Multimodal Investigations into Ancient Lived Experiences

*Laura Nissin (University of Helsinki)*

*Ella Peltonen (University of Oulu)*

*Benjamin Kämä (University of Oulu)*

*Mikko Mäkitalo (University of Oulu)*

*Aleksi Vuorinen (University of Oulu)*

Sensations, often regarded as purely physiological phenomena, are profoundly shaped by cultural and historical contexts. Without a nuanced understanding of the past sensorium, our knowledge of ancient societies remains incomplete. The "sensory turn"—a research approach aimed at a

holistic understanding of the past—has gained significant traction in recent years, offering new insights into how sensory experiences influenced ancient lives (see, e.g., Skeates and Day 2019).

In classical archaeology, vision has traditionally dominated research on the spatial design of domestic and urban environments. Influenced by the "Spatial Turn," pioneering studies in Pompeii during the 1980s and 1990s focused on visual aspects of space, including sightlines, visual axes, and the role of decorative elements like wall paintings and mosaics in shaping social spaces. However, space is not configured by sight alone. The increasing recognition of the other senses has led to a shift in the study of ancient environments, with sensory-focused research emerging over the past decade. This evolving approach considers how to best investigate past sensory perceptions, emphasizing the multisensory nature of human experience.

The emerging sensory-related research has brought about a wide range of methods to study ancient perception. Archaeology has long employed experimental methods, such as reconstructions and scale models of ancient architecture, to deepen the understanding of past spaces. Digital 3D modeling and other approaches utilizing natural sciences and computational methods are a rapidly growing area for simulating sensory experiences. Complementary to these approaches are embodied, experiential techniques that have become sought after in sensory archaeology. Such methods draw on the bodily experiences of researchers to reconstruct past sensations, facilitating a more inclusive and comprehensive understanding of the ancient sensorium. Betts (2017,3) suggests that recreating models of sensory evidence should be the first step in sensory research before delving into the individual and cultural significance of these perceptions.

This paper presents ongoing work from the Making Sense(s) of Roman Neighborhoods project, which explores how sensory experiences shaped daily life in Roman and Campanian domestic and urban spaces. The project examines the sensory dimensions of ancient coexistence by studying Roman

neighborhoods through various sensory perspectives. Our work establishes a methodological framework for reconstructing ancient sensescapes using digital twins. Case studies include the House Wooden Partition III,11 in Herculaneum and the House of Marcus Lucretius IX,3,5 in Pompeii, alongside their surrounding neighborhoods and streetscape. LiDAR scans of these sites were conducted in November 2024, forming the foundation for our sensory analysis.

This paper will focus on three key aspects of our research:

1. **Lighting Conditions:** We will discuss the use of LiDAR scanning to model the lighting conditions in House Wooden Partition III,11 and investigate their effects on the visual experience of space.

2. **Touch and Movement in Ritual Contexts:** Focusing on the crossroad altar in Pompeii VI, 14,17 at the intersection of Via Stabiana and Via Della Fortuna, we will examine the tactile experiences of individuals during religious ceremonies, using LiDAR scans brought into Unreal Engine to model human movement and the effects of crowding.

3. **Acoustic Environments:** We explore the acoustical properties of ancient spaces using convolution signal processing and binaural acoustic impulse responses to study how sound propagated within buildings and how external sounds influenced the interior soundscape. This method has been trialed at a Finnish historical site, and we will present our initial findings while outlining plans for extending this methodology to Roman contexts.

Ultimately, our goal is to form a more comprehensive understanding of how sensory experiences influenced the design and use of domestic and urban spaces. By distinguishing sensory experiences, we can gain deeper insights into the interrelationships between cultural norms, spatial use, and physiological needs in the ancient world.

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## 188. Archaeology of the Intangible through Movement and Touch

*Willeke Wendrich (Polytechnic University Turin)*

Most of our knowledge of the past is based on tangible cultural heritage and yet, the aspiration of archaeologists and historians, is to understand the aspects of the past that are intangible: ways of life, identity, relations, cultural memory, beliefs, traditions and innovations. Intangible Cultural Heritage (ICH) is centred based on knowledge, usually of an older generation, that holds the cultural memory and elements of identity of entire populations. Knowing how to speak and understand (language), knowing how to make (crafts, cuisine), knowing how to be (values, religion) and what to do (rituals, behaviour) are invisible and yet perhaps not entirely intangible. The central element that is part of this are learning how to move and touch. A teacher who tries to convey an action, might say “Let me show you”, while in fact what (s)he says is “Let me make you feel what it should feel like”. It requires the transfer of body knowledge, which inseparably integrates physical and mental activities, experience, memory, dexterity, skill and endurance.

Recording movement and touch is the starting point of understanding body knowledge, the integrated body-mind experience that is transferred in ancient and modern apprenticeship. By analysing video recordings of skilled and un-skilled present-day makers it has proven to be possible to relate the level of skill with the end product, not by considering “badly made” objects

as being the work of an apprentice, but by recording micro-variables in the present-day products that can also be recognized in ancient materials. Part of the current research project is to use VR techniques, haptic suits and eye-tracking visors to record the process of skilled makers for elements of movement and touch that cannot be analysed through video and audio alone. Through video it is possible to record the moments and intensity of work-eye contact, while VR headsets have greatly refined this with eye-tracking. Video allows for gauging working rhythm, while a high-end haptic suit records the (dis)similarity of repetitive movements, amount of pressure, shifting of body weight, and coordination of the entire body. Furthermore, haptic “recordings” can be used to have an un-skilled maker wearing a haptic suit more or less experience aspects such as the movements, handling of materials and amount of force used by a skilled maker, a novel way of conveying “let me make you feel what it should feel like”.

## 196. From Visibility to Perceptibility: A Deep Learning Framework for Horizon Profile Analysis at the Jin Dynasty Ritual Site of Baomacheng

*Zehao Li (University College London)*

Conventional visibility analyses in landscape archaeology typically focus on the binary presence or absence of sightlines, seldom addressing the perceptual qualities of what is actually seen. This study proposes a computational framework that shifts the analytical focus from visibility to horizon perceptibility, aiming to quantify how ancient observers may have experienced terrain enclosure, skyline morphology, and visual connectivity with sacred mountains.

Baomacheng, a confirmed Jin dynasty state-level ritual site associated with the worship of Changbai Mountain’s Tianchi crater lake, serves as the case

study. The framework generates systematic observation points within a 70 km radius around Tianchi using SRTM digital elevation data. For each point, custom algorithms compute 120° directional horizon profiles oriented toward the sacred mountain, capturing paired sequences of skyline elevation angles and horizon distances. These parameters encode terrain enclosure, vertical prominence, and spatial openness. The horizon profiling algorithm operates by sampling elevation data at fine azimuthal increments (e.g., every 0.5°), tracing lines of sight until reaching local horizon points, and recording both the distance and elevation angle for each sample. This method allows for the creation of high-resolution, directionally consistent horizon signatures for every observation point.

To analyze these profiles, a dual-channel temporal deep learning architecture integrating one-dimensional convolutional neural networks (CNN) and long short-term memory (LSTM) networks will be developed. The CNN component functions as a local feature extractor, identifying abrupt transitions such as peaks, saddles, ridgelines, or depressions that may influence visual prominence. The LSTM component, on the other hand, models the continuous, sequential flow of skyline geometry, capturing the temporal structure of horizon variation as one “moves” along the azimuth. Together, this hybrid architecture treats horizon profiles as temporal sequences with hierarchical features, enabling the detection of subtle patterns that may reflect culturally significant perceptual cues.

The research design incorporates three validation strategies: a). Comparative analysis of ritual sites: Baomacheng’s horizon signature will be compared with other confirmed Jin dynasty ritual sites to determine whether state ceremonial centers share distinctive perceptual characteristics, such as specific skyline rhythms or levels of visual enclosure. b) Statistical evaluation against control points: Randomly sampled observation points will serve as controls, allowing for statistical testing to assess whether ritual sites occupy visually privileged locations or exhibit horizon morphologies significantly different from the surrounding landscape. c). Correlation with terrain classes and

ritual hierarchy: Detected horizon clusters will be mapped against terrain categories (e.g., plateau, valley, ridge) and historical classifications of site hierarchy to examine whether particular perceptual patterns correlate with ceremonial function or status within the state ritual system.

This computational framework advances landscape analysis in several ways: it conceptualizes horizons as temporal sequences rather than static viewsheds; it translates subjective perceptual qualities into reproducible quantitative metrics; and it provides a scalable approach applicable to ritual landscapes worldwide. By integrating horizon morphology with deep temporal modeling, this research demonstrates how computational methods can bridge the gap between spatial analysis and phenomenological experience in archaeology. Furthermore, the framework offers potential for cross-cultural applications, enabling comparative studies of ritual landscapes in diverse topographies and historical contexts.

## 209. Visual Communication on ancient public squares: 3D vector visibility analysis

*Alexander Braun (University of Cologne)*

Using computational methodologies to investigate the visual experiences ancient observers could have had is nothing new. (Paliou 2018) Observational and quantitative methods in 2D, 2.5D, and 3D applications are already established. Mostly however, quantitative approaches in a 3D environment are applied in small scale. The project presented here, “Visual Communication Strategies on Hellenistic and Roman Squares”, sought to adapt and apply the possibilities of computational visibility analyses to a large-scale investigation of public, representative built environments.

In the Greek and Roman worlds, the public squares – the agorai and fora – were the central nexus of their respective communities. They were the centres of communication, trade, politics, law, and religion. They provided a



reference point for the collective self-conception of their societies by presenting their history, achievements, constitutions, and social order. This was achieved through architecture and applied images that defined the public space. These features however, were also, how Tonio Hölscher put it quite aptly, defined by the spaces these media of communication were placed (Hölscher 2018, 254).

With the underlying assumption that these public spaces were intentionally created the question, the sought after visibility analysis was supposed to answer, was how and with which underlying strategies different actors created these public spaces in regards to visibility and meaning. What an observer was presented and how it was presented. The actors responsible for the built environment had to balance the competing interests of benefactors, who sought distinction, and the community, which aimed to maintain equality among its citizenry.

To achieve this goal, a workflow for large-scale quantitative vector-based 3D visibility analysis was developed to investigate the afforded and prominent features of the built environment in public squares. The 3D vector visibility analysis is a GIS based tool created for large-scale urban planning. However, it can be adapted to function in relatively smaller spaces. It enables quantitative analysis and comparison of visibility distributions within a given spatial context (Braun 2019/20).

For the analysis, indexed vector lines can be created between Observer Points and Target Points to represent potential sightlines a human observer might have been able to form from their position in space. These sightlines can then be tested against the geometry of the 3D environment and validated. While the methodology shows promise, it has drawbacks in terms of computational power and data storage requirements. Nevertheless, it enables the user to analyse what parts of a built environment was potentially visible to an observer in a 3D environment and how frequently such features were made able to see.

In the case of agorai and fora this approach enables to investigate the prominence of features of the complex, planned ensembles of buildings and statues. These computational results must in a next step, be interpreted with the

knowledge of the built environment and which messages different parts were meant to communicate.

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## 458. Exploring Medieval Sacred Soundscapes: Digital Tools and Methods for the Archaeology of Sound, Hearing, and Listening

*Zorana Đorđević (University of Barcelona)*

Understanding how sound shaped human experience in the medieval Christian world requires an interdisciplinary approach that bridges the physical, cultural, and perceptual dimensions of hearing. This paper outlines the research landscape of the medieval archaeology of sound, hearing, and listening, and highlights current and emerging interdisciplinary collaborations.

The soundscape of a sacred site—whether a monastic complex, parish church, or pilgrimage route—cannot be understood through visual or textual

sources alone. Sound structured ritual life, mediated spiritual experience, and organized spatial and social relations within religious communities. Yet, the sonic past is inherently ephemeral. To study it onsite, we focus on medieval churches and monastic sites that remain largely unchanged and still practice traditional rites, providing rare chances to observe continuous sound practices. Building on published and ongoing research, the first part of this paper explores how acoustic measurements, acoustic modelling, sound mapping, tonal analysis, and psychoacoustic testing can illuminate the auditory experience of medieval sacred sites.

An archaeoacoustic approach is based on in situ acoustic measurements of medieval churches. The methodology includes recording impulse responses (IRs) and analyzing key acoustic parameters (such as reverberation time, clarity, and definition). The Hilandar Monastery katholikon on Mount Athos serves as a paradigmatic case. As a building that has remained largely unchanged since the medieval period, it provides an exceptional setting for investigating the medieval acoustic imprint. The measured data reveal how the architecture's balanced reverberation supports the intelligibility of Orthodox chant. In addition to measuring IRs, church modelling in specialized acoustic software (such as Odeon or EASE) enables a deeper examination of churches that have changed over centuries, revealing how their acoustics have evolved. An example of the Church of Lazarica (Serbia) demonstrates how the dome's geometry modulates the distribution of sound energy, creating immersive auditory effects aligned with the theological ideals of Byzantine worship [1].

The acoustic analysis of outdoor sacred soundscapes—the larger auditory environments of monasteries, pilgrimage routes, and valleys, digital sound mapping tools (such as Sound Mapping Tools, Archaeoacoustic Toolkit) linked to GIS are employed to model how sound signals from bells, semantra, and other sound-making instruments are audible across the landscape. Using published studies that combined field measurements and geospatial modelling, the paper shows how sound propagation defined the auditory

boundaries of sacred territories. The results reveal that the audibility of large percussion instruments played in a Christian context, demonstrating that acoustic mapping complements visual archaeology and allows us to visualize how sound structured movement, ritual participation, and community identity in medieval topographies.

Another methodological axis involves the acoustic characterization of historical sound-making instruments, particularly bells and wooden idiophones. To understand how such instruments contributed to the soundscape, the tonal and spectral properties of medieval bells can be analyzed using specialized software such as Wavanal. A case study from Valdres (Norway), involving 10 medieval church bells, revealed that each bell had a unique tonal structure, suggesting that their distinct acoustic signatures enabled communities to recognize the “voice” of their own parish [2]. The findings indicate that medieval bell founders did not tune bells in modern terms, but achieved perceptually distinct, locally meaningful tones. This acoustic individuality reinforced the bond between sound, place, and identity, demonstrating how medieval soundscapes were as much socially as physically constructed.

The psychoacoustic listening tests use auralization techniques to simulate how sound would have been experienced in reconstructed spaces or to compare the experience of different church acoustics. It has been shown that listeners perceive differences in reverberation and timbre as strongly tied to affective and spiritual responses. For example, increased reverberation has been associated with sensations of awe and transcendence, corresponding to theological notions of divine presence in medieval worship. The paper reviews these experimental studies and discusses their potential for future applications in museum settings and in virtual reconstructions, where auralization serves as both an analytical and a communicative tool.

Together, these four methodological strands—architectural acoustics, landscape acoustics, instrumental acoustics, and psychoacoustics—constitute a comprehensive framework for the digital study of sacred sound. Each

provides distinct yet complementary insights into how medieval people heard sound in religious life. The paper also critically assesses the limitations of each approach. Acoustic measurements can only capture the current state of preservation (not the exact historical acoustics) and are complemented by acoustic modelling. Sound mapping depends on accurate terrain and atmospheric data, whereas psychoacoustic testing often reflects modern, culturally conditioned listening habits. Acknowledging these limits is crucial for maintaining methodological transparency and theoretical rigor.

In the second part, the paper turns toward the interdisciplinary prospects that these approaches open for future research. Archaeoacoustics intersects productively with art history by offering a sensory complement to iconographic and architectural analysis, highlighting how sound interacted with visual imagery and spatial symbolism. In museology and heritage studies, digital sound reconstructions can enhance exhibition design by making intangible aspects of heritage—such as historical soundscapes—audible to contemporary audiences. Within neuropsychology, collaborations could explore how historical acoustic environments shape perception, emotion, and cognition, and how physiological responses relate to cultural interpretation. However, to examine how medieval people experience these sounds, it is essential to include the history of emotions and what Barbara Rosenwein defined as “emotional community.” [3] Finally, the integration of these disciplines contributes to the broader discourse on intangible heritage, aligning with UNESCO’s recognition of ritual sound-making as part of living cultural practice.

All of the potential interdisciplinary collaborations are only the first next step in exploring the archaeology of sound, hearing, and listening, but certainly not the final destination. By bringing together digital tools and interdisciplinary methodologies, this research maps potential connections that would advance the archaeology of sound, enabling us to begin bridging the gap between past and present forms of hearing and listening.

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- [3] Barbara H. Rosenwein, *Emotional Communities in the Early Middle Ages* (Cornell University Press, 2006).

## S11: Reframing Cultural Properties Rather than as “Relics of the Past” but as “Objects that Stimulate Modern People’s Perception, Sensibility, and Meaning-Making”

*Fujita Haruhiro, Niigata University of International and Information Studies*

*Kawano Kazutaka, Tokyo National Museum*

**Location:** Hörsaal 01

**Session Format:** Standard

- Background of this session

This proposing session is a continuous one of the session “Cognitive Mind” organized and held at CAA 2025, of which we enforced the session by adding EEG/ERPs components, for better understanding of body reactions against stimuli and emotional categories.

- VR and MR from instant 3D view to eye fixation experiment with emotion and impression

VR (Virtual Reality) and MR (Mixed Reality) represented a significant advancement by enabling viewers to see and simulate things that are not normally visible. Artefacts converted to 3D can be easily visible by VR/MR equipment, therefore one can obtain instant experience of viewing ancient artifacts.

Microsoft HoloLens2 is capable of capturing the viewer’s gaze data using its built-in cameras and sensors. This data includes the 3D coordinates of the fixation point, the direction of the gaze, and the fixation duration (saccades and fixations), serving as indicators of where a person’s potential cognition is directed on an object. By projecting the duration of gaze fixation on the surface of the object as color-graded information, it can be visualized as a 3D heatmap.

- Measuring cognition using SD Method

As an experimental method for extracting the mental images people have when viewing objects, the Semantic Differential (SD) method is widely used in psychological testing. This method involves providing pairs of simple sensory impression adjectives, such as “beautiful-ugly,” for subjects to rate on a scale. The SD method serves as crucial information to analyze how people perceive objects as stimuli through many simple sensory impression adjectives. A research paper using this method is now published as a proceedings of CAA [1].

- Reconstructing the Cognition Using Deep Generative Models

After a long period of stagnation, machine learning experienced a major turning point with deep learning for image recognition in 2012. Over the past 12 years, advancements in deep learning models have led to cognition analysis capabilities far exceeding human abilities. Recently, these models have been applied to cognition analysis as part of information psychology. By analyzing sensory impressions of subjects viewing artifacts along with data on these objects, deep cognition models offer new insights.

- Prediction of Emotional Response Categories Using Event-Related Potentials (ERPs)

Event-related potentials (ERPs), which capture the temporal responses of the brain to visual stimuli, contain features that reflect differences in stimulus categories and cognitive processing, serving as key indicators for emotion classification and semantic comprehension. For visually presented object groups—such as Jōmon pottery and clay figurines—that differ in shape and semantic interpretation, repeated ERP measurements make it possible to construct models that predict the category of emotional responses to stimuli based on electroencephalographic (EEG) data. In July 2025, emotional label measurements were conducted with a total of 306 participants in Japan and Malaysia. Given the observed fact that many participants recorded gaze trajectories associated with a single emotional label, we became confident that extracting ERPs from EEG measurements synchronized with such single

emotional labels would enable the development of models capable of predicting emotional response categories [2] [3].

• The Need for Cultural Property Cognition Studies Session  
Cognitive cultural property studies, deeply intertwined with experimental psychology and cognitive information processing, is a crucial field for exploring human psychology and the cognition through archaeological artifacts and sites. However, aside from the presentation proposed by the authors at CAA2024, no relevant research was identified.  
While it is impossible to directly investigate the cognition of ancient people, it is considered feasible to reconstruct their cognition and mental images under the assumption of commonality with modern human cognition, which were proposed by Burner and Matsumoto. Therefore, this group of founders and organizers proposes a Cultural Property Cognition Session, as a continuous from one session held in CAA 2025.

Possible investigations and methodologies:

- 3D views of artifacts by VR/MR equipment and investigations on observers' perception
- VR/MR practices for regional historical education
- VR/MR exhibition as digital museum
- Eye and gaze tracking methodologies for cognitive investigations
- Electroencephalographic (EEG) / Event-Related Potentials (ERPs) studies
- Any cognition related investigations and methodologies
- Deep learning models/deep generative models on cognition

References:

[1] Fujita Haruhiro et al. (2025) Analysis of Sensory Impression Factor Structures of Jomon Potteries through a Semantic Differential Method Viewing 3D Models on MR equipment

[2] Sano T., Shi J., Kawabata H. (2024) The differences in essential facial areas for impressions between humans and deep learning models: An eye-tracking and explainable AI approach

[3] Sano T., Kawabata H. (2024) Neural responses to perceptual and sexual ambiguity in facial images: an ERP and time–frequency analysis

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|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 16:30 – 16:50 | 35.Digitized Yet Hidden: FAIRifying Archaeological Archives through Vision and Language Models<br><i>Kateryna Lutsai (UFAL); David Novák*; Dana Křivánková*; Pavel Straňák (UFAL); Petr Pajdla*; Ronald Harasim*; Olga Lečbychová*</i><br><br>*ARUB                                                                                                  |
| 16:50 – 17:10 | 204. Archaeological Heritage as Cultural Memory: Observing Its Imprints from Antiquity to the Medieval Period – The Cases of Aigai and Teos<br><i>Ozlem Atalan (Manisa Celal Bayar University); Elif Suyuk Makakli (Isik University)</i>                                                                                                             |
| 17:10 – 17:30 | 231. Re-Imagining Archaeological Space: Sensory Perception and Digital Mediation<br><i>Elif Suyuk Makakli (FMV Isik University); Özlem Atalan (Manisa Celal Bayar University)</i>                                                                                                                                                                    |
| 17:30 – 17:50 | 239. Deep Generative Model of Human Emotion on Cultural Heritage Trained from Analytics of Human Gaze, Emotion Mapping and Verbal Impressions of Holographic Jōmon Artefacts<br><i>Haruhiro Fujita (Niigata University of International and Information Studies); Hou Yang Lu (University of Technology Petronas); Kwang Hooi Yew (University of</i> |

*Technology Petronas*); Hiroyuki Sasaki (Niigata University of International and Information Studies); Lili-ana Janik (University of Cambridge); Toru Miyao (Niigata Historical Museum); Simon Kaner (Sainsbury Institute for Japanese Cultures and Arts)

**17:50 –  
18:30**

Discussion

## 35. Digitized Yet Hidden: FAIRifying Archaeological Archives through Vision and Language Models

*Kateryna Lutsai (UFAL)*

*David Novák (ARUB)*

*Dana Křivánková (ARUB)*

*Pavel Straňák (UFAL)*

*Petr Pajdla (ARUB)*

*Ronald Harasim (ARUB)*

*Olga Lečbychová (ARUB)*

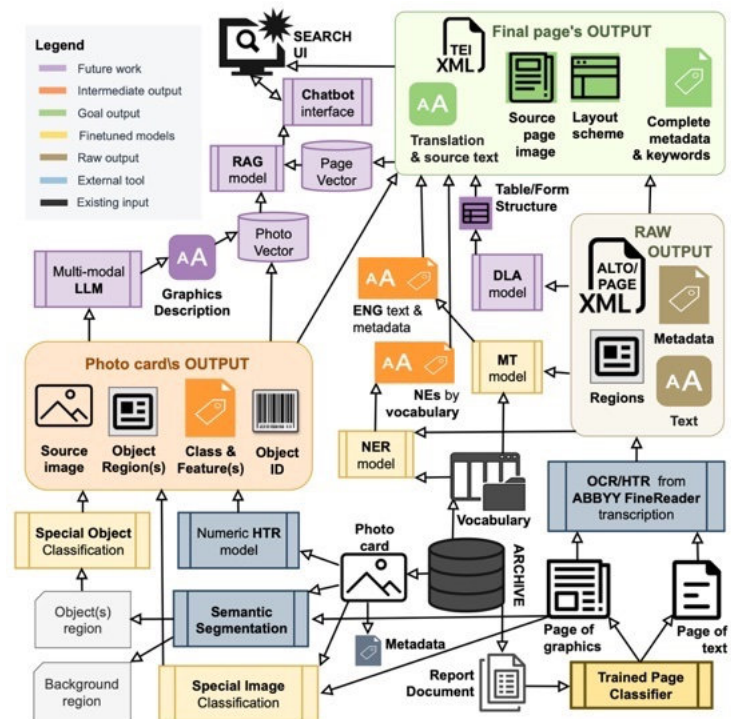
We present a compact, reusable suite of digital-research workflows designed to improve Findability, Accessibility, Interoperability, and Reuse (FAIR principles) for large institutional archives of scanned documents and photographs created in the 20th and early 21st centuries. The workflows combine content-specific page classification, selective OCR/HTR processing, and vocabulary-driven NLP to boost (meta)data quality in a Czech digital repository of archaeological fieldwork and related discovery services. We are sharing resources designed to help archivists and researchers streamline targeted analysis while minimizing the irrelevant processing of pages.

Many heritage collections hold high-resolution scans of paper-born materials with little or inconsistent metadata. This legacy material, like handwritten notes, machine-typed reports, photocards, maps, drawings, and mixed-content pages, presents a dual problem: (1) it is valuable but hard to discover, and (2) modern off-the-shelf recognition tools often fail on century-old or repeatedly re-scanned pages that exhibit folds, stains, noise, and atypical layouts. To address these gaps, we developed workflows that first systematize page images by high-level content (table, photograph, drawing/map, plain text, mixed/handwritten cutouts, etc.). Knowing a page's content allows selective application of specialized tools (OCR, HTR, object classification, or manual review), saving compute and improving overall downstream quality. A short, domain-adapted lexicon (field-specific Czech terms translated to English) supports vocabulary-driven labeling and later metadata expansion so extracted entities map to stable controlled values.

We assembled and annotated a dataset of almost 50,000 scanned pages mapped to 11 semantic content classes, hosted in a LINDAT repository; accompanying training code, README, and prediction utilities are publicly available (prepackaged for easy use). For image-based page sorting, we fine-tuned a range of backbones, including transformers (DiT, ViT), convolutional networks (EfficientNet2, RegNetY), and hybrid image-text (CLIP) models, to capture both layout and visual cues. Model evaluation includes accuracy numbers and confusion matrices per class (predicted vs. true), while the trained checkpoints and evaluation scripts are published for reproducibility. The content-specific classifiers provide a practical systematization of collections that substantially reduces unnecessary processing: pages routed to targeted tools require fewer retries and yield higher-quality outputs than a one-size-fits-all pipeline. We also found that contemporary Document Layout Analysis (DLA) frameworks, like DeepDoctection using Google's Tesseract for OCR and Facebook AI Research's detectron2 for structured data recognition, trained on clean digital PDFs often misidentify tables and miss text blocks on heavily degraded archival pages; this confirms the value of a front-end content classifier tuned on historical scans to gate further processing.



When pages are classified as text-containing, we run OCR/HTR selectively - in our experiments, we used ABBYY FineReader for automated OCR extraction (ALTO XML outputs) and measured language and quality characteristics with LanguageID and a causal-LM perplexity probe by distilgpt2 to filter reliably extracted text from noisy results. Noisy handwritten segments are flagged for more specialized HTR (e.g., finetuned Kraken/PERO-style workflows) or manual transcription. Moreover, we implemented lightweight shell and Python “glue” scripts to parse XML outputs, extract plain text, and compute simple XML-element statistics across directories; a student-developed ALTO viewer that maps XML to the JPEG page image and allows editing is available for demonstrations.



## 204. Archaeological Heritage as Cultural Memory: Observing Its Imprints from Antiquity to the Medieval Period – The Cases of Aigai and Teos

*Ozlem Atalan (Manisa Celal Bayar University)*

*Elif Suyuk Makakli (Isik University)*

### 1. Introduction

Archaeological heritage, beyond its physicality as ancient remains, constitutes a dynamic vessel of cultural memory and continuity (Halbwachs 1992; Nora 1989). Through the persistence of spatial patterns, material practices, and symbolic meanings, the physical remnants of past civilizations become catalysts for the self-definition of later communities. The concept of lieux de mémoire—places where memory crystallizes (Nora 1989)—is essential for understanding how ancient sites and reused architectural elements (spolia) operate as mnemonic anchors across time.

In Anatolia, the layering of civilizations produces a visible palimpsest where new identities are inscribed onto pre-existing urban and architectural frameworks. Monumental centers such as Aigai and Teos, both in Western Anatolia, reveal not only the durability of physical structures but also the transmission of intangible meanings related to spatial order, craftsmanship, and cultural symbolism. The re-employment of ancient materials and spatial hierarchies demonstrates how archaeological heritage actively shapes later architectural and cultural expressions (Michetti 2018).

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### 2. Theoretical Background: Archaeological Heritage and Cultural Continuity

Maurice Halbwachs's theory of collective memory emphasizes that societies reconstruct their pasts in response to contemporary identities and needs (Halbwachs 1992). In this sense, archaeological remains function as material

mediators of memory, reinforcing the continuity of collective historical consciousness. Complementing this, Pierre Nora's notion of lieux de mémoire situates memory in physical space, suggesting that when living traditions fade, material remains assume the role of remembrance (Nora 1989).

Within architectural discourse, these ideas manifest through practices of spolia, where ancient materials are consciously re-appropriated—not solely for economic convenience but as symbolic gestures of continuity, transformation, or legitimacy (Michetti 2018). The incorporation of Hellenistic and Roman fragments into Byzantine or medieval constructions exemplifies a sustained dialogue with the past—material, ideological, and mnemonic.

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### 3. Archaeological Heritage and Urban Development in Later Periods

The influence of archaeological heritage transcends static preservation; it informs urban morphology, spatial organization, and aesthetic codes in subsequent eras (Kafadar 1995; Çelik 2003). In Western Anatolia, the structural templates of ancient settlements shaped medieval urbanism, dictating orientations, hierarchies, and building materials. The reuse of ancient columns, friezes, and inscriptions in Byzantine and Ottoman contexts often entailed reinterpretations of their symbolic meanings (Michetti 2018).

This process created hybrid spatial identities in which the ancient and the medieval coexisted within an evolving narrative of place. Transformations such as converting temple precincts into churches or incorporating ancient walls into new fortifications illustrate the dynamic negotiation between permanence and change. Archaeological heritage thus emerges not as static residue but as an active participant in shaping urban and cultural continuity.

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### 4. Case Studies: Aigai and Teos

The ancient city of Aigai in present-day Manisa exemplifies how material remains continued to shape cultural landscapes well into the medieval and Ottoman periods. Excavations document the systematic use of spolia in Byzantine and early Ottoman constructions, particularly within civic and religious buildings (Aigai Excavation Team 2023). Reused column bases, capitals, and

marble blocks demonstrate both pragmatic reuse and a symbolic attempt to connect contemporary identities with the authority and prestige of antiquity. In Teos, near Seferihisar, archaeological findings indicate extensive reuse of Hellenistic and Roman elements in later phases of construction. Şükrü Atik (2017) identifies both economic and aesthetic motivations guiding these practices, reflecting a sustained engagement with ancient heritage. Diler (2015) highlights settlement continuity across the Seferihisar region, showing how ancient materials acted simultaneously as structural resources and cultural signifiers bridging the classical and post-classical eras.

Köse and Kadioğlu (2020) interpret the architectural fabric of Teos as a multi-layered urban history, where restoration, adaptation, and memory interlace. Their findings resonate with Şimşek's (2021) interpretation of Ionian cities as dynamic cultural landscapes, in which architectural heritage served as an active agent in shaping collective identity.

Together, Aigai and Teos demonstrate that archaeological heritage was not merely inherited but actively reinterpreted. Processes of reconstruction, appropriation, and adaptation reflect a deliberate effort to preserve both tangible and intangible dimensions of memory—sustaining cultural landscapes across centuries.

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## 5. Discussion and Implications

This study proposes a theoretical and methodological framework for understanding archaeological heritage as a continuum of memory, embodied through material and spatial transformations. The cases of Aigai and Teos illustrate how the re-employment of ancient materials and design principles acted simultaneously as practical mechanisms of continuity and as symbolic assertions of cultural legitimacy.

From a methodological standpoint, the integration of digital documentation and computational mapping, central to the CAA community, offers promising avenues for expanding this inquiry. Techniques such as GIS-based spatial analysis, 3D reconstruction, and digital heritage visualization can trace material and spatial continuities that are difficult to discern through conventional archaeological methods.

Ultimately, this research seeks to bridge theoretical discourse and digital practice. By applying computational archaeology to questions of cultural memory, we can better understand how material traces embody the persistence of meaning over time. The intertwined histories of Aigai and Teos reveal that archaeological remains are not passive artifacts but active agents in the formation of collective memory—shaping the evolution of architectural and urban identities from antiquity through the medieval era.

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### 231. Re-Imagining Archaeological Space: Sensory Perception and Digital Mediation

*Elif Suyuk Makakli (FMV Isık University)*

*Özlem Atalan (Manisa Celal Bayar University)*

This paper examines how architectural space within archaeological contexts is perceived, represented, and reinterpreted through digital media. Building on the notions of spatial narrative and embodied perception, it explores how digital representations transform the emotional and sensory engagement with historical environments. The study discusses how architectural thinking—with its focus on materiality, atmosphere, and human experience—can inform new modes of interpreting archaeological heritage in virtual domains.

The research aims to evaluate the visual and narrative strategies employed in digital heritage production and adopts a qualitative, interpretive methodology that compares different representational approaches. It focuses particularly on how the architectural qualities and sensory atmospheres of archaeological sites are reproduced—or lost—within digital environments. A critical analysis is developed on how aerial imagery, close-up visuals, or drawing conventions such as plans, sections, elevations, and silhouettes mediate light–shadow relationships, temporal variables, environmental interactions, and spatial stratification. This comparison exposes the divergence between on-site bodily experience and digitally mediated spatial perception, questioning how sensory depth may be diminished or over-aestheticized in virtual heritage narratives.

The paper positions archaeological space not merely as a documented historical remnant but as a living spatial experience that continues to provoke

contemporary processes of perception, sensibility, and meaning-making. Through this lens, it highlights the interpretive role of architecture in bridging the tangible and the virtual, the past and the present—offering a reflective framework for re-imagining how heritage is sensed and represented in the digital age.

### 239. Deep Generative Model of Human Emotion on Cultural Heritage Trained from Analytics of Human Gaze, Emotion Mapping and Verbal Impressions of Holographic Jōmon Artefacts

*Haruhiro Fujita (Niigata University of International and Information Studies)*

*Hou Yang Lu (University of Technology Petronas)*

*Kwang Hooi Yew (University of Technology Petronas)*

*Hiroyuki Sasaki (Niigata University of International and Information Studies)*

*Liliana Janik (University of Cambridge)*

*Toru Miyao (Niigata Historical Museum)*

*Simon Kaner (Sainsbury Institute for Japanese Cultures and Arts)*

This study redefines cultural heritage not merely as “relics of the past” but as experiential resources that stimulate contemporary human perception, affect, and meaning-making. It aims to elucidate how people perceive and respond to cultural artifacts as sensory stimuli by analyzing gaze behavior, emotional states, and spontaneous verbal expressions during embodied experiences. Using Microsoft HoloLens 2, 306 Japanese and Malaysian participants engaged with 3D holograms of cultural artifacts within mixed reality environments during June and July 2025. Their gaze trajectories, emotion classes, and impression-related utterances were recorded for cognitive and affective scientific analysis.

The cosine similarity values for each pottery feature were consistently high ( $> 0.95$ ) in cosine similarity except for pottery with nail-engraving which is lower (0.8997). The lowest similarity of pottery with nail-engraving, suggesting that this specific decorative feature may evoke more divergent emotional interpretations across cultures, possibly due to differing cultural associations with texture or symbolic meaning.

Comparison of Jōmon pottery vs dogū reactions from Japanese and Malaysian participants showed some difference for pottery with the cosine similarity of 0.9779 that might be attributed to the difference in “Interesting” responses, Malaysian participants showed 8.5% higher “interesting” and 5.2% higher for “feel nothing” than Japanese participants. While difference of emotions of “scary”, “strange” and “beautiful” were within 3% for both groups.

Dogū reactions showed a greater difference than pottery reactions (0.9613). The lower similarity is attributed to the difference in reaction of Malaysian participants to Dogū with higher “Interesting” and “Beautiful” when they are compared to Japanese participants with higher “Strange” and “Scary” responses. This may imply that both groups paid attention to the same parts but have different emotional responses. This finding is reinforced by the Jensen-Shannon Distance of Dogū eye gaze heatmap between Japan and Malaysia participants (mean = 0.248270, lower = more similar).

Clustering by average emotion with Japanese participants showed a distinct grouping of Dogū (cluster 8) and flame-like decorated pottery (cluster 7). From the graphs grouped by feature, “Beautiful” emotion is highest (48.6) for flame-like decoration as well. Whereas, Dogū were dominated by “Strange” and “Scary” responses.

Clustering of Malaysia data was less distinct, with Dogū split between “Cluster 0” and “Cluster 5”, and fire shaped pottery mostly in “Cluster 1” and “Cluster 3”, due to a varied response overall with only “Beautiful” emotion for flame-like decorations (41.5%) going over 40%.

The result of nil effects of decorative attributes and typology of 85 potteries on both emotion event counts and duration of all emotion classes indicate that those Japanese and Malaysian participant groups did not distinguish the

decoration and shape differences or paid no attention on such details, as most of participants in both groups were nearly first experience to view those ancient artefacts, unfamiliar objects for them at all.

This serves as inputs to train a deep generative model that generates human gaze heatmap, emotion labels, and impression text on unseen Jōmon pottery artefacts. Finally, emotion representation of transcripts were scored with cross-encoder models by framing the task as a zero-shot classification task with the emotion labels and transcripts text. The generated emotion and heat maps showed some matching in “Scary,” “Strange,” but some wrong generation in “Interesting” and some over estimations in gaze heatmap.

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## S12: Data Management Plans in Practice – Expectations, Implications and Real-World Experiences

*Lizzie Scholtus, Institute of Prehistoric and Protohistoric Archaeology, Kiel University*

*Steffen Strohm, Department of Computer Science, Kiel University*

**Location:** Hörsaal 03

**Session Format:** Standard

In recent years, **Data Management Plans (DMPs)** [1] have become an integral part of project proposals in archaeology and beyond. Promoted by funding bodies, institutional policies, and a growing awareness of open science, they aim to ensure transparency, reusability, and long-term accessibility of research data. However, while DMPs are widely recognised as a necessary instrument in digital research workflows, their implementation in the context of active archaeological research often reveals gaps between formal requirements and practical realities.

In former sessions and roundtables we discussed good practices in handling research data. Some raised issues were located outside of research itself: lack of funding to hire RDM staff; lack of prioritization in the proposal phase and after the project. In order to move forward, we would like to address those practical issues, which are realistically in reach and can be improved, through thorough discussion with researchers and RDM practitioners.

This session will critically explore the practical use of DMPs in archaeological research, answering the following main question: How can we improve DMPs in practical research in order to make them more accessible in the beginning, more applicable throughout the project and transparently assessable towards the end.

The session aims to provide a balanced perspective on the benefits, challenges, and evolving expectations around DMPs. On the one hand, they offer potential for better planning, coordination, and reproducibility; on the other,



they often introduce additional overhead, especially for smaller teams or projects without dedicated support. The need for structured training, clear responsibilities, and dynamic adaptability in the face of evolving project scopes is increasingly evident. While much of the discourse around DMPs focuses on policy and infrastructure, this session will emphasise practical, case-driven experiences.

Throughout the session, we aim to foster an open and constructive exchange between all participants and audience, discussing relevant actors and roles (see Figure) involved in data management:

1. **Funders** specifying expectations,
2. **Researchers and subproject teams** who must interpret and implement DMPs in specific research contexts, and
3. **Collaborators and institutions**, academic or otherwise, who share responsibility in managing, curating, and reusing data.

The session will be structured unconventionally, combining short talks and longer discussion. It will be divided into two parts. In **Part 1**, contributors will deliver a short talk (see details below), followed by questions and room for discussion focusing on specific issues raised in each case. This structure is designed to move quickly through multiple perspectives while allowing for reflection and clarification. In **Part 2**, we will open the floor for a broader discussion. Audience members will be invited to share their own insights, experiences, and concerns—whether they have worked with DMPs themselves or are preparing to do so.

We encourage participants to provide feedback that reflect on the role and reality of DMPs within their own projects — regardless of whether those experiences were positive, negative, or ambivalent. The short talks (5-10min) should cover major aspects of:

- What kind of project was it, and what role did the DMP play?

- Who was responsible for creating, implementing, and evaluating the DMP?
- Were external specialists involved?
- What challenges arose during the creation or application of the DMP?
- Was the DMP adapted over time, and how?
- Were data and results ultimately made available as initially planned?
- What types of training or institutional support were available—or lacking?
- How were problems with funders, collaborators, or data infrastructure handled?
- What lessons were learned, and how could future DMP practices improve?

We encourage researchers at all levels and from all domains of and around archaeological research to submit **abstracts** (max. 300 words) addressing their experiences with DMPs from a perspective utilising (some of) the points listed above. Abstracts should focus on concrete experiences rather than theoretical frameworks, and we welcome both success stories and critical reflections. The goal is to build a realistic picture of how DMPs function on the ground – and discuss how they might evolve to better serve the needs of active archaeological research.

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| <b>12:00 –<br/>12:20</b> | 41. Introduction to Data Management Plans in Archaeology and Digital Humanities |
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*Steffen Strohm (Kiel University); Lizzie Scholtus (Kiel University)*

**12:20 – 12:40** 316. Building A Practical Framework for Heritage Data Management: Perspectives from the Maeasam Project  
*Orhun Uğur (University of Cambridge); Stefania Merlo (Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM), University of Cambridge); Faye Lander (Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM), University of Pretoria)*

**12:40 – 13:00** 57. Data Management Plans in Priority Programme (SPP) 2143 "Entangled Africa". Research Data Management Experiences in the Project FAIR.rdm  
*Lukas Lammers (University of Cologne, Data Center for the Humanities); Eymard Fäder (University of Cologne); Felix Rau (University of Cologne, Data Center for the Humanities)*

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## 41. Introduction to Data Management Plans in Archaeology and Digital Humanities

*Steffen Strohm (Kiel University)*

*Lizzie Scholtus (Kiel University)*

Data Management Plans (DMPs) have become an integral and mandatory component of archaeological research within the framework of Open Science. They serve as the central instrument to ensure compliance with the FAIR principles (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al. 2016), thereby guaranteeing the transparency, reusability, and long-term

preservation of research data. This relevance is continuously amplified by national (e.g., DFG, ANR) and international (e.g., ERC, Horizon Europe) funding guidelines.

This submission may serve as an introductory overview to the session and builds upon successful preceding discussions held in 2024 and 2025, which already exposed shortcomings: from a lack of personnel resources for Research Data Management (RDM) to insufficient prioritisation both during the proposal phase and once the project is underway. To address these challenges practically and move the discussion forward, this talk will include hands-on experiences and open the field for discussion. We aim to compare the expectations of funding bodies with the realities of archaeological research practice, thereby making DMPs more accessible at the start, more applicable throughout the project, and transparently assessable towards the end.

**\*\*Selected Frameworks and Own Experience\*\***

The presentation provides a specific contribution by highlighting the inconsistent requirements of funders and the resulting practical difficulties as a foundation for linking additional perspectives and discussions with the audience. We will first present the formal frameworks for DMPs across the primary funding landscapes of the authors: Germany (specifically DFG guidelines and CRC projects), France (national agencies and institutional policies), and at the European level (ERC grants). We will then subject our own experiences within these contexts to discuss:

- Germany (CRC Project): The focus here is on integrating RDM into large-scale projects, where data provision requirements are often less explicit and compliance is less formalised than at the EU level, raising questions about long-term binding commitment.

- France: Here, national and EU requirements are often merged, demanding specific institutional support, particularly in dealing with heterogeneous humanities data.

- European Level (ERC): ERC funding mandates the creation and continuous updating of a DMP (typically after six months), which necessitates high administrative effort and a strict focus on the FAIR principles throughout the project's duration.

These case studies will demonstrate that the requirements for written DMPs are highly variable, and the lack of common structure and vocabulary (Williams et al. 2017) leads to ambiguities. Moreover, our experiences show parallels with the findings in Digital Humanities (DH), where the DMP process, if not integrated into work practices from the outset, can be perceived as a compulsory, bureaucratic exercise (Poole 2020).

#### **\*\*Implications for Practical Research\*\***

The challenges arising from these discrepancies affect the entire research community. A lack of standardisation of requirements in DMPs not only hinders the comparability and reusability of data but can also negatively impact data quality itself, as essential missing perspectives (e.g., data quality assurance metrics) remain unaddressed in the plans. We will engage with contributors and the audience to actively discuss the discrepancy between expectation and reality of DMPs: How can DMPs be transformed from a mere compliance document into an effective management tool that truly serves researchers? And how can researchers transform DMPs into a useful research tool?

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## **57. Data Management Plans in Priority Programme (SPP) 2143 “Entangled Africa”. Research Data Management Experiences in the Project FAIR.rdm**

*Lukas Lammers (University of Cologne, Data Center for the Humanities)*

*Eymard Fäder (University of Cologne)*

*Felix Rau (University of Cologne, Data Center for the Humanities)*

Since 2018, the German Research Foundation (DFG) has funded SPP 2143 “Entangled Africa: Inner African relations between the rainforest and the Mediterranean, around 6000–500 years ago”. The program comprises a total of 13 projects, 11 of which use different methods to investigate various topics in specific (time) periods on the African continent. Besides the coordination project, the FAIR.rdm project holds a special position as it does not conduct field research but examines research data management in archaeology and provides practical RDM support to the other projects.

In the project, a wealth of experience and insights have been gained. A report on everyday experiences was published a few years ago (Lammers et al. 2023) and a detailed final article is pending (Fäder et al. 2026).

In 2018, the DFG policies on RDM were relatively vague. Therefore, at the beginning of SPP 2143, FAIR.rdm conducted a survey on the actual DMPs in the projects, which revealed a very heterogeneous level of knowledge among researchers in this area. As a result, FAIR.rdm endeavored to bridge the gaps through workshops and consulting services. Meanwhile, however, the research work in the projects also got underway and took some unpredictable turns because civil wars and the COVID-19-pandemic made the designated research areas inaccessible.

In the end, almost none of the original DMPs were implemented or updated by the researchers. Instead, many projects relied on the expertise of FAIR.rdm, where a DMP for each project is maintained as a “living document” and where the most important information about the respective research data and current agreements is recorded.

This approach supports ongoing project work better than the previously considered use of an RDMO instance (<https://rdmorganiser.github.io/>), the setup and ongoing maintenance of which would have required considerable project resources. After all, a DMP, like good research data management in general, must support scientific work and provide a positive added value.

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## 316. Building A Practical Framework for Heritage Data Management: Perspectives from the Maeasam Project

*Orhun Uğur (University of Cambridge)*

*Stefania Merlo (Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM), University of Cambridge)*

*Faye Lander (Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM), University of Pretoria)*

Documentation is a central tenet in the archaeological discipline and a necessary aspect in the preservation of heritage (Beck 2013). Without such documentation an increasing number of heritage sites risk becoming completely invisible due to escalating anthropogenic and natural threats. It is safe to say that every field archaeologist acknowledges the critical importance of accurate recording from the initial data collection to cataloguing finds and provenience, to storage and presentation. These principles are an integral part of any given research data lifecycle.

There has been a concerted effort placed on the development of Data Management Plans (DMPs), data lifecycle models and associated tools for application in archaeological research and for the management of digital heritage repositories. However, the uptake of researcher DMPs across different regions has been uneven and there continues to be numerous challenges with implementing these in practice (Fadlelmola et al. 2021). In the context of Africa, many researchers face challenges that include funding and resource constraints, lack of research data management knowledge and finding appropriate, practical, guidelines on how to implement DMPs that align with FAIR data principles. Africa-based researchers may also face restricted accessibility to relevant tools due to infrastructural requirements and internet connectivity. This can be seen, at least in part, as a continuation of the post-colonial imbalances in knowledge production and access. Another challenge with the application of DMPs is that they are often designed for the needs of

single projects and tend to reflect a centralised approach. Considering the uniqueness of each project and the ethical and political dimensions of data ownership in multi-partnered collaborations such models often remain insufficient.

This paper presents a practical response to these challenges using a case study from the Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM) Project. The MAEASaM project is working in collaboration with national museums and heritage authorities across eleven countries in Africa to establish a secure and accessible digital geospatial repository of sites and monument records using the Arches open-source platform. Within this collaborative environment, it became essential that the project find a way to develop a coherent and transparent system to manage diverse datasets and individual workflows produced by different researchers based across multiple institutions.

In this paper, we introduce our data management framework including the development of a file organisation schema to structure digital heritage data, aligning with the FAIR (Findable, Accessible, Interoperable, Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, Ethics) principles and considers the OAIS (Open Archival Information System) framework for data dissemination and archiving.

A key principle of the framework is that not all data is openly shared. Sensitive or personal information such as heritage locations and/or details that are linked to specific communities are carefully protected. In practice, this means that certain datasets remain accessible only to the original contributors or within defined project boundaries, while archival copies are retained locally to ensure long-term custody and sovereignty over data. We propose that by using this approach we can reframe data management as more than just a technical workflow to become a form of knowledge exchange. Through documentation practices, contributors gain data management skills and

methodological awareness that can be transferred to future heritage projects.

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## S13: If I Had a Hammer, I'd 3D-Scan It: Computational Approaches for the Analysis of Tool Artifacts

*Anastasia Eleftheriadou, Institute for Digital Cultural Heritage Studies, Ludwig Maximilian University of Munich, Germany*

*Guillermo Bustos-Pérez, Department of Human Origins, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany*

*João Marreiros, Laboratory for Traceology and Controlled Experiments (TraCEr) at MONREPOS Archaeological Research Centre and Museum for Human Behavioural Evolution, Leibniz-Zentrum für Archäologie (LEIZA), Neuwied, Germany*

**Location:** Hörsaal 01

**Session Format:** Standard

Technology can be defined as a socially transmitted, multidimensional system that integrates raw materials, operational sequences, behaviors, cognitive processes, and the knowledge and intentions underlying the creation and use of products (Kozatsas, 2020; Schiffer and Skibo, 1987). Tools, as tangible expressions of this system, offer insights into human behavior, as their design, manufacture, and use can reflect adaptive responses to ecological, demographic, and sociocultural conditions (Foley and Lahr, 2003; Hovers, 2012; Kuhn, 2020).

Recent advances in computational methods have transformed the ways archaeologists document, analyze, and interpret tools made from materials such as stone, bone, wood, and metal (e.g., Calandra et al., 2019; Courtenay et al., 2020; Luncz et al., 2022; Marreiros et al., 2020). The adoption of high-resolution 3D modeling has grown steadily since the early 2010s, with applications now well established across a range of artifact types (Courtenay et al., 2019; Proffitt et al., 2023; Wyatt-Spratt, 2022). Since 2018, the use of machine and deep learning techniques has likewise expanded (Bellat et al.,

2025; Eleftheriadou et al., 2025; e.g., Courtenay et al., 2024; Luncz et al., 2022; Sferrazza, 2025). Together, these developments are broadening the scope of archaeological studies, enabling comparative analyses across diverse raw materials, chronological periods, and geographical regions.

This session invites papers that apply or critically engage with computational methods in the analysis of lithic, bone, wood and metal tools. We encourage contributions using (but not limited to):

- **3D and surface-based methods:** Photogrammetry, laser scanning, micro-CT, and surface metrology for documenting and analyzing tool morphology and use-wear.
- **Geometric morphometrics:** 2D or 3D landmark-based approaches, including outline and shape analyses.
- **Machine learning and AI:** Supervised and unsupervised methods (e.g., SVMs, tree-based classifiers), deep learning approaches (e.g., convolutional neural networks), for tasks such as segmentation, classification, and pattern recognition.
- **Computer vision and image analysis:** Techniques such as edge detection, segmentation, and texture quantification.
- **Simulation and modeling:** Agent-based modeling, biomechanical simulations, and virtual experiments.
- **Spatial and network analysis:** Geographic information systems (GIS) and network analysis methods.
- **Open science, databases, and interoperability:** Development of FAIR-compliant datasets, ontologies, and reproducible workflows.

We particularly welcome studies that address known challenges in the field, such as equifinality, small or imbalanced datasets, taphonomic overprinting, and the integration of heterogeneous data types. Case studies, methodological advances, experimental validation, and theoretical reflections are all encouraged. By bringing together archaeologists, material scientists, and computational specialists, this session demonstrates how advanced digital



methods can reveal new insights into human behavior through the study of tool production and use.

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| <b>14:00 – 14:20</b> | <p>20. An Interpretable and Reproducible Deep Learning Approach for 3D Morphological Ceramic Classification: A case study of Sue ware in Japan<br/> <i>Wataru Tatsuda (UCL); Ryo Hori (Nagoya University); Kimiyasu Morikawa (Georgia Institute of Technology); Hayata Inoue (Nagoya University)</i></p>                                                                                                                                                                                                                                                                                          | <b>15:20 – 15:40</b> | <p>154. Bronze axes, landmarks, outlines, 3D models, and traces. Are we able to identify objects from the same casting moulds?<br/> <i>Marcin Maciejewski (Maria Curie-Skłodowska University); Agata Hałuszko Maria Curie-Skłodowska University; Archeolodzy.org Foundation); Maksym Mackiewicz (Archeolodzy.org Foundation); Kamil Nowak (Austrian Archaeological Institute); Agnieszka Pawlina (Maria Curie-Skłodowska University)</i></p> |
| <b>14:20 – 14:40</b> | <p>32. Controlled flake experiments, 3D scanning, landmarking and the extraction of features for a better understanding of flake formation and analysis<br/> <i>Guillermo Bustos-Pérez (Max Planck Institute for Evolutionary Anthropology); Shannon McPherron (Max Planck Institute for Evolutionary Anthropology)</i></p>                                                                                                                                                                                                                                                                       | <b>15:40 – 16:00</b> | <p>184. Fine-tuning Vision Transformers for Lithic Micro-wear Classification: A Deep Learning and Explainable AI Approach<br/> <i>Paolo Sferrazza (LEIZA)</i></p>                                                                                                                                                                                                                                                                            |
| <b>14:40 – 15:00</b> | <p>78. Simulating and Analyzing Core and Flake Assemblages using a Virtual Knapper<br/> <i>Shannon McPherron (Max Planck Institute for Evolutionary Anthropology)</i></p>                                                                                                                                                                                                                                                                                                                                                                                                                         | <b>16:00 – 16:30</b> | Coffee break                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>15:00 – 15:20</b> | <p>147. If I had a Hammer, I'd model the resulting fracture: Experimental and Morphometric Approaches to Flake Formation<br/> <i>Tamara Dogandžić (Leibniz-Zentrum-für-Archäologie, MONREPOS Archaeological Research Centre and Museum for Human Behavioral Evolution, Neuwied); Li Li (ICArEHB - The Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour Universidade do Algarve, Faro); Guillermo Bustos-Pérez (Max Planck Institute for Evolutionary Anthropology, Leipzig); Shannon McPherron (Max Planck Institute for Evolutionary Anthropology, Leipzig)</i></p> | <b>16:30 – 16:50</b> | <p>213. Deep Learning for 3D Point Cloud Classification of Lithic Artifacts by Reduction Strategy<br/> <i>Li Li (Chinese Academy of Sciences); Shannon McPherron (Max Planck Institute for Evolutionary Anthropology); Will Archer (Florisbad Quaternary Research Station, National Museum Bloemfontein)</i></p>                                                                                                                             |
|                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>16:50 – 17:10</b> | <p>257. From Strikes to Knowledge. Experimental Knapping as Source for modelling Operational Sequences of Lithic Artifact Productions in 3D<br/> <i>Florian Linsel (Free University of Berlin); Hubert Mara (FU Berlin)</i></p>                                                                                                                                                                                                              |
|                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>17:10 – 17:30</b> | <p>280. Identifying series in European Late Bronze Age metal mass production through production techniques: the SerialKey project</p>                                                                                                                                                                                                                                                                                                        |

*Léonard Dumont (Université Bourgogne Europe); Fabrice Monna (Université Bourgogne Europe); Josef Wilczek (Sorbonne Université); Nicolas Navarro (EPHE); Ivan Josipovic (Ghent University); Matthieu Boone (Ghent University)*

**17:30 –  
17:50**

284. Deep Learning for Automated Classification of Contact Materials and Tool Motion in Lithic Use-Wear Analysis : Insights from Archaeological and Experimental Data  
*Anastasia Eleftheriadou (Ludwig Maximilian University of Munich (LMU)); Youssef Djellal (Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), Universidade do Algarve); Abdeljalil Bouzouggar (Institut National des Sciences de l'Archéologie et du Patrimoine); Shannon P McPherron (Max Planck Institute for Evolutionary Anthropology); João Marreiros (TraCEr, Laboratory for Traceology and Controlled Experiments at MON-REPOS Archaeological Research Centre and Museum for Human Behavioural Evolution, LEIZA)*

**17:50 –  
18:10**

347. Quantitative 3D Analysis of Shipwright Tool Marks: Preliminary Results from the Late Antique Ma'agan Michael B Shipwreck  
*Aleksandra Wiese\*; Deborah Cvikel\*; Gadi Herzlinger\**

*\* University of Haifa*

**18:10 –  
18:30**

Discussion

## 20. An Interpretable and Reproducible Deep Learning Approach for 3D Morphological Ceramic Classification: A case study of Sue ware in Japan

*Wataru Tatsuda (UCL)*

*Ryo Hori (Nagoya University)*

*Kimiyasu Morikawa (Georgia Institute of Technology)*

*Hayata Inoue (Nagoya University)*

### 1 Introduction

This study presents an innovative deep learning-based approach—with a cutting-edge deep learning model, PointTransformer (Zhao et al. 2021)—for the morphological classification of 3D point cloud data of ceramics. Point Transformer has proven to be inherently well-suited for point cloud analysis. The compatibility between point clouds and Transformers arose because Transformers operate on vectors, and point clouds are typically represented as collections of vectors owing to their intrinsic properties. Unlike natural language processing, which relies on word embeddings, point cloud analysis can be applied directly without preprocessing. Point Transformer outperformed other effective deep learning models (e.g., MVCNN, VoxNet, PointNet++, and DGCNN) in the shape classification task with the reliable 3D datasets, ModelNet40. Through this study, we demonstrate that our deep learning implementation can capture subtle morphological variation, offering archaeologists a flexible, transparent, and reproducible method for ceramic classification that can be extended to other research purposes.

This article focuses on a case study of Sue ware from the Sanage kilns in Japan, dating from the 8th to mid-9th century. Sue ware is a type of unglazed stoneware produced and used mainly from the 5th to the 10th century in Japan (Raith et al. 2016). Sue ware in the Sanage kiln was selected as the target material for two reasons. First, its typology, based on standardised shapes formed during its manufacturing process, suits a morphological

classification task. Second, the discussion of eating practices provides an appropriate archaeological context for this approach. Some scholars state that dish-type vessels declined while bowl-type vessels became common in the late 9th century, reflecting a shift of eating habits from using hands to spoons or chopsticks. Previous studies, relying on empirical classification or the machine-learning approach on 2D silhouettes, have failed to establish a robust, objective morphological classification necessary for discussing the correlation between vessel form and dietary practices. To address this, we introduce Point Transformer to classify Sue ware directly from the 3D point cloud data.

## 2 Materials

The five typical types of Sue ware were selected for this study—Dish Cap (DC), Dish Body with Ring Base (DBR), Dish Body (DB), Bowl (B), and Plate (P). DC contained 390 samples, whereas P had only 58. DBR, DB, and B had similar counts: 154, 129, and 186, respectively. In total, point clouds of 917 Sue-ware samples (1,024 points each) were collected via optical scanning and photogrammetry. They were manually assigned the respective type label by hand to use as the input data. We also selected six ambiguous samples between DB and B, which the previous 2D outline-based approach failed to capture the subtle differences, to interpret the model's behaviour on borderline cases.

## 3 Methods

- Implementation: 3D shape classification using Point Transformer (Figure 1-1)
- Evaluation: k-fold cross-validation with  $k = 5$
- Visualisation: Principal Component Analysis (PCA) and hierarchical clustering (dendrogram)
- Interpretation: the BubbleX implementation, which generalizes Grad-CAM from 2D images to unstructured 3D point clouds, and was extended to the architecture (Matrone et al. 2023)

## 4 Results

### 4.1 Evaluation

Our model successfully classified 917 vessel samples into labelled classes with high accuracy (average macro F1-score: 0.9320). For DC, DBR, and P, the model achieved almost perfect precision and perfect recall, resulting in F1-scores of 0.9975, 0.9766, and 0.9761, respectively. However, DB and B showed different patterns. DB exhibited a precision score of 0.8535 and a lower recall score of 0.8166. Conversely, the scores of B show the opposite trend: the recall score of 0.8961 was higher than that of 0.8646.

### 4.2 Visualisation and Interpretation

PCA revealed overlaps between B and DB in features captured by the deep learning model, whereas the dendrogram showed class-wise hierarchy and the proximity of B and DB (see Figure 1-2,3). Figure 1-4 presents two saliency maps for B and DB predictions on an ambiguous sample. Consequently, the model correctly categorised five of the six borderline specimens.

## 5 Archaeological discussion

The results support the hypothesis that there may be a correlation between the shape transition and eating habits. If, during the 8th to mid-9th century, the functions of the two classes (B, DB) were not clearly distinguished, it is understandable that the boundary of them is ambiguous. This implies that people in ancient Japan used the two types of tableware interchangeably during this transitional period. This pattern may arise because the current dataset consisted solely of kiln-site material dated to the 8th to mid-9th century. Broader sampling from other consumption sites and other periods—specifically, before and after the transition—will be required to trace the full trajectory of shape change.

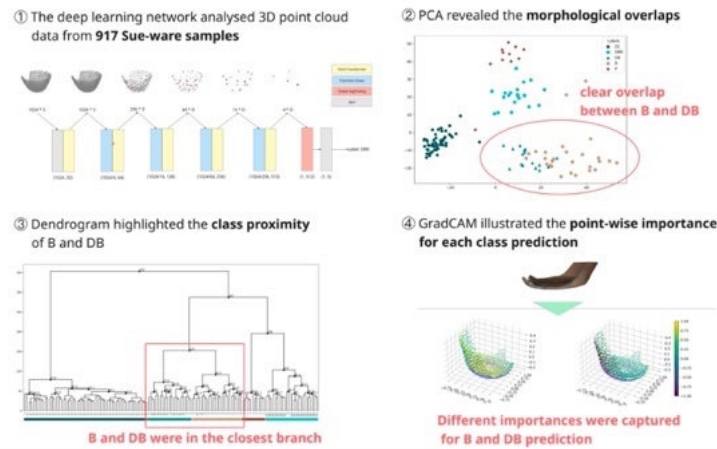


Figure 1: Graphical Abstract

## 6 Methodological discussion

The transparency of this approach transforms the model from a black box into a tool that archaeologists can explore and apply to established typological criteria. The PCA and dendrogram provided a clear visualisation of the model's decision-making process. The saliency map for 3D geometry makes this approach unique and significant because it cannot be employed for 2D-based approaches. The areas of focus indicated by Grad-CAM suggests that the model may classify based on regions that local experts also consider important. Moreover, this approach is computationally and financially efficient while maintaining high performance. Using only 1,024-point input clouds eliminates the need for costly GPUs, high-precision 3D sensors, or extensive data storage, enhancing accessibility for researchers with limited resources.

Regarding the robustness of the model, the model seemed to acquire the ability to classify pottery even though the dataset was unbalanced and included ambiguous and incomplete samples. Nevertheless, the imbalanced dataset may affect the results since the dataset proportion was maintained in the training dataset during the training process. We attributed this study

primarily to the standardised wheel-thrown pottery, which likely contributed to the effectiveness of the classification result. Although the dataset comprised 917 samples, typical archaeological contexts often offer smaller dataset. The current implementation would ideally require at least 50 samples per class, with 100 or more being preferable for optimal performance. Researchers may supplement their data with our open-source dataset or apply data augmentation techniques.

## 32. Controlled flake experiments, 3D scanning, landmarking and the extraction of features for a better understanding of flake formation and analysis

*Guillermo Bustos-Pérez (Max Planck Institute for Evolutionary Anthropology)*

*Shannon McPherron (Max Planck Institute for Evolutionary Anthropology)*

Lithic flakes are some of the most common remains from archaeological sites. They are present since the earliest stone tool industries up until modern stone tool users. Flake production informs about multiple features of past hominin groups. These features range from early hominin motor control and cognitive abilities; possible learning skills and levels of technicality among past groups and individuals; the evolution, internal variability and adaptation of different lithic techno-complexes through time and space; and site occupation patterns and raw material economy (Toth and Schick, 2018). Because of their wide range of applications, important attention has been paid to drivers of flake formation and morphology.

Controlled experiments into flake formation and morphology allow for a high level of standardization (through the use of homogeneous materials, standardized core forms and machines for the actual flaking) while variables of interest are modified individually. This makes it possible to verify the individual effect of each variable (and their interactions) on flake formation and

morphology, along with providing additional data usually not available or stable (force, hammer morphology, AOB). When the resulting experimental collections and data are combined with digital approaches (landmarking, 3D geometric morphometrics, digital measurements, etc.) an improved understanding of drivers of flake formation and morphology is made possible. Additionally, this combined approach opens the possibility to explore new variables and methods for the analysis for these experimental flakes. The results on these controlled experiments are then tested again in freehand experiments. Free hand experimentations confront models of flake production and morphology with the increased variability of actual stone tool production as we expect to find in the archaeological record. This two-step process allows models to be validated along with the proposed variables and methods for flake analysis while exploring their distributions among different known populations (expert and novice knappers, different knapping strategies, etc.).

An example of this contrast between controlled and freehand experiments is the formulation of the external platform angle (EPA), platform depth (PD) and angle of blow (AOB) model (Li et al., 2023). This model, developed in controlled experiments, indicates that these three variables are responsible for a significant part of the morphological and mass variability in flakes ( $r^2 = 0.83$  when predicting cube root of flake mass). However, when this model has been tested in freehand experiments, it has a much lower predictive power, with contradictory results regarding the importance of some of its variables. One potential explanation of this difference comes from the difficulty in accurately measuring EPA on actual flakes (as opposed to flakes coming from controlled experiments). Flakes usually present an irregular topography on their dorsal surface, resulting in multiple EPA measurement options for the same flake. This problem has long been noted by different lithic analysts, with different proposals on how to approach it. These proposals ranged from do not include this variable in the analysis, only including it when it was clearly visible, or using trigonometric functions and projections of angles.

An alternative but perhaps analogous feature present in most flakes is the angle between the platform and the edge of the flake, hereafter referred to as the platform-edge angle (PEA; see also bilateral platform angle (BPA) as proposed by Pope et al., 2017). 97 glass flakes were knapped under controlled conditions from hemisphere cores presenting a convex surface with no effective EPA (a way of idealizing the problem presented often in freehand experimental flakes). These flakes were scanned and 3D landmarked. A regression plane was then fit to the edge and platform landmarks to then calculate the above-mentioned angle. Additionally, the same procedure was applied to flakes from the Dibble et al. controlled experiments flakes (which do show a clear EPA because of the core design).

Both experimental collections allow an exploration of what variables are driving the PEA and its relationship with flake mass. The results for the hemisphere flakes (where the curvature remained constant) indicate that PD is the main driver of PEA ( $r^2 = 0.615$ ), and that this angle can also be used to predict flake mass ( $r^2 = 0.862$ ). However, in the Dibble et al. flakes where EPA is available, EPA becomes the main driver of PEA ( $r^2 = 0.837$ ) rather than PD ( $r^2 = 0.214$ ). Additionally, like EPA, PEA alone is not a good predictor of flake cube root of mass ( $r^2 = 0.049$ ) in the Dibble et al. flakes.

For the hemisphere flakes, adding PEA as a predictor of flake mass in a multiple linear regression with PD and AOB resulted on an improvement of all accuracy metrics ( $r^2$  improves from 0.86 to 0.94; MAE improves from 0.16 to 0.1; RMSE improves from 0.2 to 0.13) and a significant difference for the median absolute of the residuals is present ( $V = 3622$ ;  $p < 0.001$ ). However, the predictive accuracy of multiple linear regression models using both variables differed in the Dibble et al. dataset. Here the model using EPA presented better accuracy metrics ( $r^2 = 0.84$ ; MAE = 0.16; RMSE = 0.17) than the model using PEA ( $r^2 = 0.78$ ; MAE = 0.21; RMSE = 0.32), with a significant difference being present for the median absolute of the residuals ( $V = 808$ ;  $p < 0.001$ ). Finally, in a test of measurement methods, among the hemisphere



flakes, measures of PEA obtained through landmarks and manual goniometers showed no statistically significant difference between groups.

These results suggest that EPA and PD are driving PEA which is then a direct driver of flake size. Although using PEA might result in a lower predictive accuracy of flake mass, perhaps it is easier than the often difficult to measure EPA. These results open the possibility of using PEA as an additional variable in lithic analysis for its role in predicting flake shape and mass and for its distribution among different populations (expert and novice knappers, different knapping methods, hammer types, etc.). These results, however, require further confirmation with freehand experiments and tests with the archaeological record.

## 78. Simulating and Analyzing Core and Flake Assemblages using a Virtual Knapper

*Shannon McPherron (Max Planck Institute for Evolutionary Anthropology)*

One of the primary methods archaeologists use for understanding how past stone tool assemblages were created is through experimental reproduction. Typically, raw materials similar to those used in the archaeological record are knapped experimentally to reproduce end-products. The fit to the archaeological record is measured not simply by the similarity of end-products produced in each case (i.e. actual and experimental) but also by assessing the character of the whole assemblage of resulting flake debris.

Replication is an effective method for gaining insights into the past technical behaviors that create the archaeological record, but there are also a number of limitations. One of these limitations is the amount of effort required to produce and analyze a large enough number of experimental assemblages that potential drivers of variability can be isolated and explored. If multiple drivers are being tested at once, for instance hammer type and raw material, the number of trials need to control for each quickly multiplies the size of the

resulting assemblages. Another limitation can be, depending on the particular variable, limits in the ability to systematically control between trials an aspect of the lithic production. Examples of this can include the size, shape and quality of the raw materials, how the knapper delivers force (e.g. the angle of blow, the contact area of the hammer), how mistakes or flaws in the material are overcome, etc.

Virtual simulation of knapping can perhaps address a number of constraints to experimental lithic production. Here a virtual knapping software previously presented at the CAA is now used to replicate an experiment conducted by Moore and Perston (2016). Their replicative experiment was designed to gain insights into the level of organization or hierarchical planning required to produce the earliest stone tool assemblages. They knapped 29 silcrete and mudstone cobbles and 30 silcrete flakes using a random number generator to select which platform to exploit after each successive strike. This resulted in a kind of least-effort flaking with no prior planning. They produced in a massive set of assemblages representing 1115 cores (because cores were analyzed after each flake removal rather than only as final products) many of which fully replicate Oldowan examples. It would be interesting to repeat their experiment with slightly modify knapping strategies (for instance, taking the largest possible flake each iteration) or to better control for the effect of initial raw material shape and size on the outcomes; however, the vast effort this would entail makes this a difficult decision in light of limited research time.

To address this issue and to replicate this work in software, 3D representations of cobbles of both standardized and varying size and shape were knapped using Virtual Knapper. We then successively increased the complexity of the reduction strategy (or rule set). For instance, initially the cores are randomly knapped. Next, a limit on the size of the flake that can be remove is applied, and later the simulation removes the largest flake (within the size limit) given a particular core configuration. The flake products and the cores are then analyzed and compared after each simulation. To automate the analysis of the cores, the flake scar orientation approach recently developed by Lin et al. (2024) is applied. Exactly replicating the Moore and

Perston experiment required the development of a method for assessing potential platforms on the cores. While ideal platforms are easily recognizable as the intersection of two faces at an angle roughly between 60 and 90 degrees, assessing these features in non-ideal cases required developing new methods.

Overall the results show how increasing the complexity of the rule set structures variability in the resulting cores and flakes, and only relatively simple rule sets are needed to produce early stone tool assemblages. This proof of concept opens the possibility to generate more varied assemblages to feed into a number of on-going efforts including creating training data for machine learning models to refit stone tool assemblages and machine learning models to segment and classify stone artifacts, studies of assemblage formation that include breakage, taphonomic loss and transport of items into and out of the virtual site, and so forth. Virtual simulation in 3D of lithic production is not a replacement for experimental studies, but it may provide a useful tool for modeling flake formation, for exploring tool manufacture and assemblage formation, and for generating virtual assemblages used to train models that will eventually be applied to actual assemblages.

### 147. If I had a Hammer, I'd model the resulting fracture: Experimental and Morphometric Approaches to Flake Formation

*Tamara Dogandžić (Leibniz-Zentrum-für-Archäologie, MONREPOS Archaeological Research Centre and Museum for Human Behavioral Evolution, Neuwied)*

*Li Li (ICArEHB - The Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour Universidade do Algarve, Faro)*

*Guillermo Bustos-Pérez (Max Planck Institute for Evolutionary Anthropology, Leipzig)*

*Shannon McPherron (Max Planck Institute for Evolutionary Anthropology, Leipzig)*

Stone tool technology provides a window into many aspects of prehistoric lives: cultural connections between groups, mobility patterns, site function, skill, and knowledge transmission, among others. Understanding the sources of variation in stone tools is, therefore, a central question in lithic studies. The size and shape of flakes detached from a core are primary observations that guide our interpretation of the variability of stone tool technologies. To understand the variability of individual flakes, we must understand how knappers control the flaking process to achieve particular outcomes.

Experimental work by experienced knappers replicating past flaking techniques and methods have made enormous contributions to this question. They reveal that manipulating different knapping parameters — such as types of hammers, preparation and shaping of core surfaces, striking angles, percussive force, platform size, platform shape, and types — results in different flake outcomes. These works directly help us to reconstruct past flaking methods, understand predetermination in flaking processes, identify skill levels, track innovations such as novel hammer uses, etc.

Controlled experiments involved flaking machines that allowed one to isolate, observe and importantly quantify the effects of individual variables and their interactions on the outcome. Results from controlled experiments show that the primary impact on flake size and shape is the angle of the core surface (exterior platform angle) and the distance from the core edge where the hammer hits (platform depth), with additional effects of the striking angle (summarized in (Li et al. 2023)).

The effect of all these variables is difficult to understand without a comprehensive model to tie them together. We return to fracture mechanics to better understand the formation of flakes and to provide a robust model of how all these variables play together to determine the final flake form and size. According to fracture mechanics studies, flake formation is divided into initiation (crack and bulb formation), propagation (fracture plane traveling through the core), and termination phases (when the fracture plane finishes intersecting the core surface) (Cotterell and Kamminga 1987). Based on data from controlled experiments, insights are gained into the effects of the

Hertzian cone, a cone of force that propagates through brittle, cryptocrystalline materials from a point of impact, on flake outcomes, particularly the crack formation (McPherron et al. 2020).

We take these results further and address the effect of the Hertzian cone on the mechanics of flake formation beyond the initial crack. In this study, we examine the initiation and propagation phases of flake formation and their impact on flake size and shape. Specifically, we examine how flakes expand beyond the platform, how a bulb forms on the interior side of the flake, the placement of the fracture plane, and the relationship between the fracture plane and the core morphology. We used flakes produced from a controlled experimental setup, built by Harold Dibble in his Laboratory for the Study of Ancient Technologies at the University of Philadelphia. This setup allowed for individual variables involved in flintknapping processes to be isolated, manipulated, and varied in order to evaluate their individual and combined effects on flake size and shape outcomes. It used a servo-hydraulic press to exert a direct force on the core, initiating a fracture. Cores used in these experiments were molded of soda-lime glass into a semispherical shape, but also molded or cut to reproduce the core morphologies from the archaeological record. In this setup, one can control different flaking variables: exterior platform angle, core morphology, hammer type, angle of blow, and, to some extent, the location of hammer strike. Data used in this study come from several experiments, each with different combinations of control variables being varied. Over 300 flakes produced in these experiments have been 3D scanned and landmarked.

Preliminary results show the continued effect of the Hertzian cone on flake shape. Together with the striking angle, the cone tilts in a way that determines the bulb size. The expansion of the flake, which by and large determines the overall shape, is driven by the morphology of the frontal surface area (exterior platform angle and the core surface) of the core and the positioning of the fracture plane. These results emphasize the importance of incorporating the first principles of fracture mechanics to build models of size and shape variability of archaeological flakes. They provide information about which principles of flaking are understood and used by past knappers,

they help reconstruct flaking techniques and methods of blank production, and further help understand the sources of variability in the archaeological record.

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### 154. Bronze axes, landmarks, outlines, 3D models, and traces. Are we able to identify objects from the same casting moulds?

*Marcin Maciejewski (Maria Curie-Skłodowska University)*

*Agata Hałuszko (Maria Curie-Skłodowska University; Archeolodzy.org Foundation)*

*Maksym Mackiewicz (Archeolodzy.org Foundation)*

*Kamil Nowak (Austrian Archaeological Institute)*

*Agnieszka Pawlina (Maria Curie-Skłodowska University)*

The Late Bronze Age Rosko hoard (Montelius period V – 950-800/750 BC; north-western Poland) differs markedly from most contemporary hoards,

which typically comprise typologically and functionally diverse artefacts. In contrast, the Rosko assemblage represents a highly selective deposit dominated by socketed axes of two closely related types that also display a high degree of metric standardisation. The hoard additionally includes casting moulds for the production of socketed axes (Maciejewski 2019), raising questions about the organisation, scale, and standardisation of metallurgical production in the Late Bronze Age and Early Iron Age.

This study addresses four interrelated research problems: (1) the number of moulds potentially used to cast the Rosko axes and the extent to which typologically and metrically similar specimens could have been produced from the same moulds; (2) whether subtle typological distinctions can be corroborated through detailed morphological and metric analyses; and (3) the functional use of axes, including the identification and variability of wear traces and the degree of wear, which contributes to the understanding of the biographies of individual objects, (4) the extent to which such diverse biographies may influence the analysis of 2D and 3D metric properties.

A total of 71 axes from the Rosko hoard and related contexts (including a second hoard and a single find), together with one two-part casting mould, are analysed using a combination of 2D analyses (Pawlina, Hałuszko, Maciejewski 2025), 3D geometric morphometrics, 3D deviation (morphometric) analysis, and wear analysis. The study compares the effectiveness of these approaches for capturing morphological and metric variability and assessing use-related surface modifications. In parallel, data acquired with two structured-light 3D scanners are evaluated to compare their performance and suitability for analysing archaeological artefacts.

The research presented here forms part of a broader project focused on hoards of metal objects from the Late Bronze Age and the Early Iron Age deposited within stone-built structures. The project operates across multiple analytical levels, encompassing fieldwork, excavation, and non-invasive investigations (magnetic survey, GPR, and UAV LiDAR), as well as desk research centred on the analysis of archival data and materials available in the public domain (for example, archival maps and LiDAR data), and studies of the metric, physical, and chemical properties of selected artefacts. The overarching

aim is to reconstruct and compare, as comprehensively as possible, the biographies of several hoards that share a similar – archaeologically defined – depositional context (Maciejewski 2023).

As noted above, the Rosko hoard differs from other assemblages of this period in terms of the selection of deposited artefacts. For this reason, understanding the processes underlying this selection is particularly important. To this end, we employ, among other approaches, computer-assisted morphometric analyses, wear analysis, which will be presented in our paper, and investigations of chemical composition and lead isotope ratios, which in the future will allow a more comprehensive understanding of the community that deposited these metal objects beneath large boulders

The research is part of a project ‘A biography of Late Bronze and Early Iron Ages hoards. A multi-faceted analysis of metal objects related to monumental constructions in Poland’ (2021/41/B/HS3/00038) funded in whole by the National Science Centre, Poland.

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## 184. Fine-tuning Vision Transformers for Lithic Microwear Classification: A Deep Learning and Explainable AI Approach

*Paolo Sferrazza (LEIZA)*

### Introduction

Functional interpretations of lithic artefacts are a central concern in prehistoric archaeology, as they provide a direct window into technological behaviour, task organisation, and cultural transmission. The microscopic analysis of use-wear traces on lithic surfaces has traditionally relied on expert-based qualitative approaches, in which classification accuracy depends strongly on the observer's experience and visual consistency. Despite advances in quantitative microscopy and multivariate statistics, the translation of complex microtopographic and textural information into reproducible categorical data remains challenging.

In recent years, machine learning and computer vision methods have shown significant potential for the automatic classification of microwear traces (Eleftheriadou et al. 2025). Convolutional Neural Networks (CNNs) have become standard tools in this domain, but their spatially limited receptive fields may restrict the integration of long-range contextual information — a key feature for identifying subtle wear patterns. Vision Transformers (ViTs), by contrast, model global attention relationships within the image and, thus, offer a powerful framework for capturing distributed textural and structural cues (Dosovitskiy et al. 2020).

The present study explores the application of a fine-tuned ViT-B/32 model to the automated classification of lithic microwear traces produced on eight distinct worked materials. The approach aims to assess both the discriminative capacity and the interpretability of transformer-based architectures in functional studies of stone tools.

### Materials and Methods

The dataset used for this study comprises 560 grayscale micrographs (8-bit PNG, 224×224 px) from 34 used flakes and 2 unused flakes, divided into eight classes corresponding to the worked materials: antler, bone, butchery (fresh meat), hide, plant, shell, wood, and unused. Each class includes an equal number of samples, with 480 images used for training/validation (80/20) and 80 only for testing. The images derive from experimentally used flint tools from diverse geographical contexts (Italy, Germany, and Morocco), as well as different brightfield microscopes and setups, ensuring variability.

All images from train/validation were normalised and augmented using random rotation, horizontal/vertical flips, and slight contrast variations to enhance robustness. A Vision Transformer (ViT-B/32) pretrained on ImageNet was implemented using the Hugging Face transformers library. The fine-tuning strategy involved unfreezing all 12 transformer blocks (97.26% of total parameters trainable; 85,060,616 / 87,461,384) and optimising the network using the AdamW optimiser with an initial learning rate of  $1e-5$ , batch size of 4-32, and early stopping based on validation loss. The classification head was adapted to eight output neurons with softmax activation.

Training proceeded for 50 epochs with performance monitored via categorical cross-entropy loss and accuracy. The final model was selected based on the lowest validation loss (epoch 10). The test phase evaluated standard metrics (accuracy, balanced accuracy, Cohen's  $\kappa$ , ROC-AUC, precision, recall, F1-score). Additionally, explainable AI (XAI) analyses were performed using attention rollout and attention flow (plus random maps as a baseline comparison) to visualise class-discriminative image regions and assess the interpretability of model decisions in relation to surface microtopography.

### Results

The model exhibited rapid convergence and stable generalisation throughout training. Validation accuracy improved steadily from 56.05% at epoch 1 to 91.58% at epoch 10, while validation loss decreased from 1.31 to 0.32. The final evaluation on the independent test set yielded: Accuracy 96.75%, balanced Accuracy 96.75%, Cohen's  $\kappa$  95.7%, AUC (macro average) 99.3%.



Per-class performance was consistently high, with F1-scores exceeding 0.90 in all categories. Perfect precision and recall ( $F1 = 1.00$ ) were observed for plant, unused, and wood classes, while slightly lower but still robust values were obtained for bone and butchery traces ( $F1 = 0.94-95$ ). These results confirm the model's capacity to discriminate wear patterns generated by different worked materials, despite a limited sample size and complex intra-class variability.

XAI visualisations further revealed that attention-based saliency maps corresponded closely to micro-polish zones and striation observed under high magnification, demonstrating the network's sensitivity to relevant tribological features. In particular, attention flow heatmaps localised activations on areas exhibiting distinctive reflectivity and directional texturing, confirming the model's interpretability and coherence with expert-based functional criteria.

#### Discussion

The present experiment demonstrates that transformer-based architectures can achieve high accuracy and explainable decision patterns in the classification of lithic microwear images. Compared with CNN models previously tested on the same dataset, the ViT-B/32 exhibited faster convergence and improved generalisation, likely due to its capacity to integrate long-range dependencies across the image via self-attention mechanisms (Dosovitskiy et al. 2021). The model's global receptive field proved advantageous for capturing the subtle interplay between surface brightness, texture anisotropy, and microtopographic transitions (from used to unused surfaces) that define functional categories.

The integration of XAI techniques provided critical interpretive transparency, bridging the gap between automated classification and archaeological/functional reasoning. The congruence between visual saliency maps and tribological markers suggests that deep learning methods, when properly fine-tuned and validated, can approximate expert visual judgments while maintaining reproducibility and scalability.

#### Conclusions

This study provides one of the first systematic demonstrations of Vision Transformer architectures applied to lithic microwear analysis. The fine-tuned ViT-B/32 achieved high classification accuracy (96.75%) and substantial inter-rater agreement ( $\kappa = 0.957$ ), confirming its potential as a robust, interpretable tool for functional analysis. Beyond performance metrics, the ability to visualise attention patterns in relation to meaningful microwear features represents a critical step toward transparent and reproducible digital traceology.

The integration of deep learning, XAI, and experimental archaeology opens new possibilities for quantitative and replicable assessments of prehistoric tool use. ViTs, by modelling distributed attention across the entire surface, offer a conceptual parallel to the holistic perceptual strategies used by experienced analysts, thereby providing both a methodological and cognitive bridge between human expertise and artificial vision.

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### 213. Deep Learning for 3D Point Cloud Classification of Lithic Artifacts by Reduction Strategy

*Li Li (Chinese Academy of Sciences)*

*Shannon McPherron (Max Planck Institute for Evolutionary Anthropology)*

*Will Archer (Florisbad Quaternary Research Station, National Museum Bloemfontein)*



Machine learning has become an increasingly popular tool in archaeology, enabling researchers to perform tasks such as classification, segmentation, and prediction. While these algorithms have been widely applied to image and numerical data from the archaeological record, relatively few studies have explored their use with 3D point cloud data of artifacts. Compared to traditional numerical, photographic, or even landmark-based data, 3D point clouds capture artifact morphology in far greater detail, providing a rich representation of shape and surface variability. To date, much of artifact shape analysis has relied on 3D geometric morphometrics, which uses landmark data to quantify morphological variation. Although this approach is well-established and effective, it remains labor-intensive. Even when partially automated, landmark placement typically requires significant manual input to ensure consistency across specimens.

Motivated by these limitations, this study applies machine learning methods that directly analyze 3D point cloud data without the need for manually defined landmarks. Recent advances in deep learning have produced architectures capable of processing unordered 3D point sets, although most have been trained on everyday objects such as furniture or household items, rather than archaeological materials.

This paper investigates the following questions:

1. Can 3D deep learning algorithms classify lithic flakes according to their reduction strategies and how do different model architectures perform on this task?
2. How robust are these models when applied to independent datasets?
3. What insights can we gain about model interpretability through critical point analysis?

Two datasets were used in this study: one for model training and one for independent testing. The training dataset consisted of 3D scans of experimentally produced flakes created by experienced knappers replicating Middle and Upper Paleolithic reduction strategies. Flakes were selected from complete reduction sequences representing three broad strategies—Discoidal ( $n = 98$ ), Levallois ( $n = 306$ ), and Laminar ( $n = 164$ ). The original models were in PLY format. Each PLY file was randomly sampled to 2,048 points,

converted to .npy format, and split into training, validation, and test sets. To address class imbalance, 10 different data splits were generated. For the independent test dataset, we used 3D flake models from Hallinan and Cascallheira's work (<https://osf.io/sj8zv/overview>). This dataset contains 178 Nubian flakes. It is expected that Nubian and Levallois flakes share morphological features., thus making them a strong external test for model generalization and robustness.

We implemented three representative deep learning architectures that operate directly on unordered 3D point clouds: PointNet(Qi et al. 2017a), PointNet++(Qi et al. 2017b), and the Dynamic Graph CNN (DGCNN, Wang et al. 2019).

Each model was trained for 40 epochs using the same hyperparameter settings and loss functions. Model performance was evaluated using overall balanced accuracy, per-class accuracy, and confusion matrices.

To explore model interpretability, we performed critical point analysis to identify points within the 3D models that contributed most strongly to classification decisions. The top 20% of points with the highest importance scores were extracted and visualized to assess spatial distribution patterns across flake surfaces.

After 40 epochs of training, all three models demonstrated promising classification performance.

- PointNet achieved class accuracies of Discoidal: 0.60, Laminar: 0.64, Levallois: 0.80.
- PointNet++ achieved class accuracies of Discoidal: 0.93, Laminar: 0.64, Levallois: 0.72.
- DGCNN achieved class accuracies of Discoidal: 0.87, Laminar: 0.68, Levallois: 0.72.

While overall accuracies were satisfactory, confusion matrices showed notable overlap between the Discoidal and Levallois classes. This pattern aligns with archaeological observations that these two reduction strategies can produce morphologically similar byproducts, and even expert analysts sometimes disagree in distinguishing them.

When applied to the independent Nubian Levallois dataset, the pre-trained models produced variable but generally positive results. For PointNet++, out of 178 total samples, the model correctly classified 175 flakes (98.3%) as Levallois and misclassified 3 flakes (1.7%) as Discoidal. For DGCNN, the model correctly classified 140 flakes (78.7%) as Levallois, while 15 were incorrectly predicted as Discoidal and 23 as Laminar. Despite being trained on a different dataset, both models demonstrated consistent sensitivity to Levallois-type morphology, suggesting their potential to generalize across assemblages. It is important to note, however, that the Nubian Levallois flakes are all end products with clear diagnostic features typical of Levallois technology; therefore, a high rate of correct classification is expected in this case.

These preliminary results demonstrate that deep learning models have the potential to effectively classify lithic flakes from 3D point clouds without relying on manually placed landmarks. The overlap observed between Levallois and Discoidal classifications underscores both the potential and the interpretive complexity of applying machine learning to lithic analysis. Rather than treating misclassifications as mere errors, these results may reflect meaningful technological continuities or shared morphological outcomes between reduction strategies. Critical point analysis will provide further insight into model behavior by highlighting which parts of the flakes contribute most to classification. Comparing these machine-derived “diagnostic zones” with those recognized by expert analysts may reveal new ways of formalizing expert knowledge or detecting previously unquantified morphological cues.

This study illustrates the potential of 3D deep learning methods to support automated analysis of lithic assemblages. Such approaches could significantly reduce manual labor, standardize morphological assessments, and enable large-scale comparative studies that were previously impractical. Ultimately, integrating deep learning with traditional archaeological expertise may lead to more reproducible and data-driven interpretations of technological variability.

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## 257. From Strikes to Knowledge. Experimental Knapping as Source for modelling Operational Sequences of Lithic Artifact Productions in 3D

*Florian Linsel (Free University of Berlin)*

*Hubert Mara (FU Berlin)*

Motivated by questions about digital classification of lithic artefacts and technologies, we are developing methods that use segmented 3D datasets to create graph representations of surface features like scars and cortex. While previous work has established the workflow for creating graph models, this article describes the process of generating the base segmentation data of surface features, e.g. cortex and scars, for method validation with the help of 3D monitored experimental knapping series of lithic artifacts.

In previous studies (Linsel et al., 2024a,b), we recreated 3D drawings of scar ridge patterns on the 3D meshes, by segmenting each surface feature into a separate label on the mesh. This can be done with different manual annotation workflows for scars or ridges respectively. The labelled data is then processed into an adjacency graph model, in which each node represents a

surface feature and an edge can be interpreted as their neighbourhood defined by the adjacent outlines of neighbouring features. This approach allows to integrate all 3D data as node or edge attributes, making them available in the data model. Therefore, a graph model includes all spatial information of the surface features, those of the adjacent outlines, network attributes and additional datasets including the manually determined temporal relation between adjacent features (Linsel et al., 2024b). In summary, a graph model includes commonly used archaeological criteria, like edge angle, which is not limited to working edges (Linsel et al., 2024a).

One of the crucial limitations comes from the base datasets that were created by hand, making an evaluation of following approaches unreliable because the resulting data will vary, depending on the chosen method and the person annotating. All manually created label datasets therefore have an interpretation bias on each stage. For example, when starting with already published drawings, which are reused for guidance of the creation of 3D annotation, the 3D annotation itself to the manually created directed graph models (similar to Harris matrices of reduction sequences), all steps rely on manual input. Hence, every stage is interpretive, so error compounds and is hard to quantify. When this data is then used for a parameter driven prediction of the relation between adjacent scars on graph models (Linsel et al., 2024a,b), the reliability of the results cannot be evaluated properly. Therefore, having ground truth data with minimal interpretation bias is needed to reliably develop segmentation algorithms and graph model based predictions of their temporal order.

We create reliable ground truth datasets that use registered meshes of experimentally created and monitored lithic cores to generate surface features as labels. From the labelled 3D models we can automatically derive a graph model by applying a change based segmentation using a novel software framework. In this context, a monitoring series consists of a single core, that is scanned during the knapping experiment, documenting single or multiple removals, that can be considered as a boolean difference operation or a form of subtraction of raw material. Due to minor inaccuracy in mesh resolution and point locations, we applied a distance based approach (closest-point

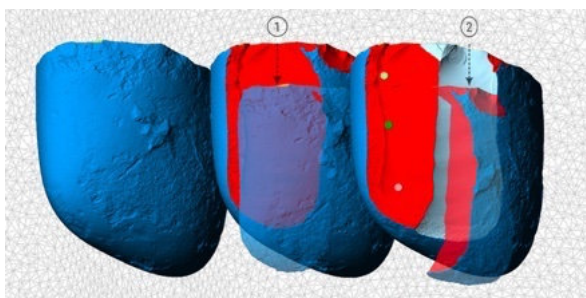
distance) that quantifies changes between successive pairs of 3D models. By applying a threshold on the distance metric, these regions are automatically labelled as newly created scars. That approach allows us to temporally order surface alterations, automatically creating a complete operational sequence and also to track each feature over the duration of a knapping experiment, and how the graph model changes. As a result the first occurrence of a surface feature, removal and alteration of surface features can be investigated. As 3D scanning artifacts are known for having an exhaustive time consumption, our software solution can handle two 3D scan settings. The first can be used with completely scanned cores and the other with partly scanned cores. Our approach further includes a more direct application of the boolean difference operation, in which a mesh is subtracted from a second mesh. This results in the creation of labelled 3D models for the removed pieces.

The last processing step relies on the enriched graphs, that include all geometric attributes and network measures, that can be used as data source for training neural networks. Because of their structure, we trained graph neural networks (GNNs) that can learn directly on graph-structured data. Two GNNs (GAT, GCN, GraphSAGE) were trained for distinguishing artefact categories, e.g. cores and flakes, and lithic technologies, e.g. bifacial and unidirectional blade core reduction.

To demonstrate the functionality of the approach, we monitored a reduction sequence of an unidirectional blade core knapping sequence from the beginning of the experiment to its complete exhaustion. Doing this allows us to extract proper ground truth data for scars as well as the graph modelling the knapping sequence. The experiment was designed to cover multiple different experimental settings, to develop an automatic annotation software, which accommodates different experiment designs. We applied both scan routines, fully and partially scanned cores, and used two objectives, scanning after each major surface change ( $> \sim 2$  cm) or after a procedural unit. Here, a procedural unit is defined by the knapper as a working step with varying amounts of removals.. The approach was additionally used on an open access data publication Lombao and Rabuñal (2019), which included 30 experimental knapping series. By applying the routine we automatically labelled

602 3D models and graph models (302 labelled cores and 300 removed pieces). The graph models are then used to train the GNNs. The performance of the best neural networks achieved F-scores of up to 0.933 for artefact type classification and 0.701 for lithic technology classification.

We provide (i) an automated change-based segmentation framework, (ii) graph modelling of operational sequences, and (iii) a ground-truth dataset to benchmark several tasks e.g. segmentation, temporal order predictions of surface features and 3D puzzling.



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## 280. Identifying series in European Late Bronze Age metal mass production through production techniques: the SerialKey project

*Léonard Dumont (Université Bourgogne Europe)*

*Fabrice Monna (Université Bourgogne Europe)*

*Josef Wilczek (Sorbonne Université)*

*Nicolas Navarro (EPHE)*

*Ivan Josipovic (Ghent University)*

*Matthieu Boone (Ghent University)*

### Introduction

The European Bronze Age witnessed an unprecedented standardization of artefacts through mass production. Casting techniques led to seriality: the production of multiple series of similar objects (Stockhammer 2017), making stylistic distinctions harder to detect, and thus making fine-grained typological classifications almost impossible. As a result, the socio-economic structure of bronze objects production remains poorly understood. By shifting the archaeological focus from the stylistic to the technological diversity of metalwork, the SerialKey project seeks to provide insights into European Bronze Age serial mass production. To that end, a new technological classification to complement typological and chemical approaches is proposed. It is based on an innovative methodology, which relies on micro-computed tomography ( $\mu$ CT) and geometric morphometrics. The aim is to identify series of artefacts cast in similar conditions and produced by the same workshop or production group. That is one of the keys to understand how metalworkers organized their industry, in terms of specialization, geographic dispersion, and mobility.

### Materials and methods

The non-invasive method to study the production techniques of bronze artefacts relies on X-ray micro-computed tomography ( $\mu$ CT). It consists in

acquiring series of 2D X-ray projections of artefacts to digitally reconstruct their volume. This enables the exploration of their inner structure (fig. 1), providing insights into their chaîne opératoire. CT scans have been performed at Ghent University Centre for X-ray Tomography (UGCT, Belgium) using the HECTOR setup, equipped with a 240 kV microfocus X-ray source (Masschaele et al. 2013).

A test sample of 90 Late Bronze Age (ca. 950-800 BC) socketed axes from Belgium is being studied before considering applying the project methodology at a larger scale. Socketed axes are common Late Bronze Age mass-produced tools found in a large part of Europe. They were serially produced, for example with reusable moulds made of stone or bronze. They included a core inserted in the centre of the mould as the bronze was cast. This core was then withdrawn, creating the socket used to fit a handle (fig. 1). This mode of production resulted in large series of hundreds or thousands of relatively well standardised artefacts. As a result, current typological frameworks often fail to identify series of objects originating from different workshops.

Socketed axe volumes were reconstructed using  $\mu$ CT with a resolution of 65  $\mu$ m. Volumes were segmented to obtain quantitative data about the porosity (pore volumes, shapes, sizes and coordinates) as well as 3D meshes of the axe surfaces.

## Results

Three main technological features are studied using data obtained through the segmentation of CT reconstructions to identify the productions of different workshops:

1. Casting quality, based on total porosity and alignment of the core within the mould, depending on the metalworker expertise and casting conditions.
2. Pore profiles, based on size, shape and spatial distributions of the pores, depending on the casting conditions.
3. Shape diversity, based on the shape of the socket. As it remains unchanged after the casting, it is possible to reconstruct the shape of the core that was placed in the mould.

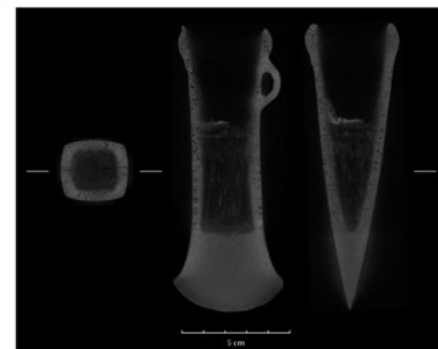


Fig. 1: Slices through the reconstructed volume of an axe from Han-sur-Lesse, Belgium. © I. Josipovic, L. Dumont

Our presentation will focus more precisely on the core shape diversity. Unlike the axe's surface, which can be significantly altered after casting, the socket remains untouched, thus offering a proxy to identify series of axes cast using similar moulds. Three-dimensional meshes of the casting cores were produced and processed using the auto3dgm R package (Boyer et al. 2014) to identify clusters of axes cast made with a similar core. As the core shape can help making the distinction between socketed axes cast with different types of cores and moulds, this feature plays an essential role in the construction of a new technological classification of socketed axes.

## Discussion

We must discuss the archaeological significance of the clustering made based on the core meshes to identify series of socketed axes originating from different workshop. A first exploration of the clustered data shows that some axes with peculiar socket shapes are well detected using Boyer's method. Some types of axes are produced using very similar cores, whereas other show a greater diversity. It suggests different consumption groups had different way to source the axes they sought.

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## 284. Deep Learning for Automated Classification of Contact Materials and Tool Motion in Lithic Use-Wear Analysis : Insights from Archaeological and Experimental Data

*Anastasia Eleftheriadou (Ludwig Maximilian University of Munich (LMU))*

*Youssef Djellal (Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), Universidade do Algarve)*

*Abdeljalil Bouzouggar (Institut National des Sciences de l'Archéologie et du Patrimoine)*

*Shannon P McPherron (Max Planck Institute for Evolutionary Anthropology)*

*João Marreiros (TraCER, Laboratory for Traceology and Controlled Experiments at MONREPOS Archaeological Research Centre and Museum for Human Behavioural Evolution, LEIZA)*

### Introduction

Use-wear analysis is a key method for studying tool function, providing insights into past human behaviour (Fullagar 2014). To address the need for more automated and standardized analysis of traces, from 1998 onward there has been a growing interest in the use of machine learning (ML), mainly for the classification of polish. Polish is a use-wear trace formed by the gradual removal or deformation of a tool's natural surface (Schmidt et al. 2020). A range of algorithms has been explored to analyze diverse use-wear traces across various raw and contact materials. Nevertheless, important gaps persist in identifying which ML models are most effective for specific tasks, and how these models make decisions and impact archaeological interpretations. This study investigates the potential of convolutional neural networks (CNNs) to support the automated classification of polish in use-wear analysis of stone tools based on contact material and direction of motion (kinematics), using both controlled experimental datasets and archaeological samples from the Middle Stone Age site of Bizmoune Cave in Morocco.

### Methods

This study included 108 grey-scale images of polish (41 experimental and 67 archaeological), later expanded through sampling and augmentation to over 900 samples, using a fully reproducible Python-based workflow. Image data were analyzed with CNN models (custom-made, DenseNet121, MobileNetV2, and ResNet50) across standard, few-shot, and cross-domain learning paradigms. Model performance was evaluated using accuracy, precision, recall, F1-score, confusion matrices, and interpretability methods (Score-CAM, Integrated Gradients, SmoothGrad, t-SNE, and UMAP).

### Results

CNN models trained on experimental data and evaluated on archaeological samples achieved accuracies of 69% for bone, 59% for hide, and 58% for wood. These results exceed the baseline accuracy (33%) expected under uniform class distribution, suggesting that the models were able to extract informative patterns from the experimental dataset that were transferable to archaeological samples. Models trained and tested exclusively on



archaeological data achieved higher accuracies (81% for bone and 73% for hide and wood), indicating that the experimental dataset could be further enhanced to capture additional parameters influencing polish formation in archaeological contexts. The classification of archaeological data based on kinematics yielded 83% accuracy for longitudinal and 72% for transversal motion, based on reference labels provided by a use-wear specialists.

#### Discussion

CNNs can effectively classify polish based on both contact material and kinematics. For models trained exclusively on archaeological data, few-shot learning outperformed standard learning, highlighting the potential of this approach in archaeology. The performance of cross-domain evaluation was slightly lower than that of models trained exclusively on archaeological data, likely due to the increased complexity and distinct characteristics of use-wear patterns in archaeological samples that are not fully captured by the experimental dataset. Nevertheless, the cross-domain models still achieved classification results well above random chance, demonstrating their potential to improve as additional data become available (Zhang et al. 2024). Some key limitations in this study involved constraints related to data diversity and quantity, as well as computational resources, which may have impacted the robustness of the results and the efficiency of the analyses.

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### 347. Quantitative 3D Analysis of Shipwright Tool Marks: Preliminary Results from the Late Antique Ma'agan Mikhael B Shipwreck

*Aleksandra Wiese (University of Haifa)*

*Deborah Cvikel (University of Haifa)*

*Gadi Herzlinger (University of Haifa)*

Tool marks preserved on ancient ship timbers provide a direct record of past shipwright behavior and technology, yet they have rarely been examined systematically. The Ma'agan Mikhael B shipwreck, dating to the Late Antique and Early Islamic transition, represents a pivotal stage in Mediterranean shipbuilding, marking the shift from shell-first to frame-based construction. Despite its excellent preservation and visible marks of saws, adzes, and chisels, no quantitative tool-mark study has been undertaken, nor for other roughly contemporary wrecks such as Tantura A or those from the Theodosian Harbor at Yenikapi. This project applies a computational 3D analytical approach to digital models of tool marks from the Ma'agan Mikhael B and Tantura A shipwrecks. High-resolution scanning protocols were developed to document fragile, waterlogged wood, producing digital meshes suitable for quantitative surface analysis. Academic software, such as MeshLab 2025.07, MeshInspector 2.5.5 and ArchCut3D v1.96 amongst others, and custom code written in MatLab R2025b are used to extract geometric features and curvature parameters to describe and compare tool-mark morphologies statistically. Experimental tool marks produced under controlled conditions serve as a comparative dataset for interpreting archaeological patterns. Integrating semantic description with quantitative measurements, the study seeks to characterize variability in tool-mark geometry in terms of tool type,

working skill, and individual craftsman. The resulting dataset and analytical framework aim to establish a reproducible catalog for future studies, advancing the understanding of ship carpentry traditions and the evolution of ancient Mediterranean shipbuilding. Ultimately, this approach lays the groundwork for identifying potential individual “fingerprints” of shipwrights through statistically significant and comparative morphometric analysis.

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## S25: How to do ROAD: An Essential Tool for Conducting Multidisciplinary Studies Related to Human Evolution

*Christine Hertler, ROCEEH Research Center*

*Andrew W. Kandel, ROCEEH Research Center*

*Christian Sommer, ROCEEH Research Center*

**Location:** Hörsaal BIG

**Session Format:** Standard

Computational analytical approaches have long been established in the study of human history, and they place increasing demands on data volume, structuring, and reliability. As a large-scale research database providing information about human evolution and cultural development, the ROCEEH Out of Africa Database (ROAD) represents an essential tool for researchers. Systematic data collection in ROAD covers Africa and Eurasia between three million and 20,000 years ago. The database contains information about 2,500+ sites and 26,000+ assemblages, with details on human fossils, their paleoenvironmental context in terms of associated fauna and flora, as well as artifacts and their behavioral and cultural interpretations (Kandel et al. 2023). Such a comprehensive warehouse of data prepares the way for integrative studies about the expansions of humans over the course of their journey through prehistoric times.

Most of the data contained in ROAD stems from 6,300+ published sources. Although the majority of data comes from scientific journals published during the last two decades, other sources include historical publications and/or data found in reports and through personal communications. ROAD also integrates data published in languages other than English including other script systems, such as Cyrillic or Chinese. ROAD is curated and maintained by the ROCEEH team.

The Research Center “The Role of Culture in Early Expansions of Humans” (ROCEEH) explores expansions of early humans. The mobility of human groups resulting in large-scale dispersal patterns represents *expansions of range*. Such range expansions reflect changing patterns of resource use, that is, *expansions of the resource space*. In turn, such shifts are driven by changing conditions in the paleoenvironment due to climatic oscillations as well as expansions in sociocultural practices, namely *expansions of cultural performances*.

The ROCEEH team designed a set of tools which enables researchers to explore data in ROAD without direct support and/or in-depth knowledge of writing SQL queries. Examples of available applications in ROAD include: ROAD Site Summary Data Sheets for each locality entered; ROAD Simple Search, an easy-to-use interface to learn more about the contents of the database; WebGIS also known as the MapModule for basic mapping functions; Ask ROAD, an application which allows users to compose queries easily; and upcoming roadDB, a library for data retrieval and analysis using the R language. We will introduce and discuss the use of these tools in a separate ROAD workshop at CAA 2026. In this standard session we invite and feature studies which have been conducted using ROAD data to illustrate the range of methods which can be applied to evaluate large datasets. Examples of the range of studies start with analyses of spatiotemporal patterns (Scerri & Will 2023), network analysis (Sommer et al. 2022) and paleoenvironmental studies (Archer 2021), but also covers diverse modeling approaches including niche modeling (Yaworsky et al. 2024), species distribution models (Timbrell 2024), and simulation-based approaches (Coco & Jovita 2025).

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| 08:30 –<br>08:50 | 193. An Overview of the ROAD Database and Its Application to the Study of Human Evolution<br><i>Andrew Kandel*</i> ; <i>Angela Bruch*</i> ; <i>Nicholas Conard*</i> ;<br><i>Miriam Haidle*</i> ; <i>Christine Hertler*</i> ; <i>Volker</i> |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

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*Hochschild\*; Zara Kanaeva\*; Jesper Borre Pedersen\*; Friedemann Schrenk\*; Christian Sommer\**

*\*Heidelberg Academy of Sciences and Humanities*

**08:50 – 09:10** 155. Tracking change through time: habitat suitability changes for the first hominins of Europe  
*Carolina Cucart-Mora (Museum National d'Histoire Naturelle,); Ana Belén Galán López (Museum National d'Histoire Naturelle); Jan-Olaf Reschke\*; Kammilla Lomborg\*; Matt Grove (University of Liverpool); Christine Hertler (ROCEEH Research Center, Senckenberg Research Institute); Marie-Hélène Moncel\**

*\* CNRS UMR 7194 HNHP, National Museum of Natural History*

**09:10 – 09:30** 84. Modelling Early Hominin Habitat Suitability in Eurasia: Integrating GIS and Machine Learning Approaches  
*Ana Belén Galán López\*; Carolina Cucart-Mora\*; Christine Hertler (ROCEEH Research Center, Senckenberg Research Institute); Marie-Hélène Moncel\**

*\* CNRS UMR 7194 HNHP, National Museum of Natural History*

**09:30 – 09:50** 59. Quantifying Landscape Learning: Integrating Archaeological and Environmental Models of Early Modern Human Dispersal in Western Eurasia  
*Jesper Pedersen (Heidelberg Academy of Sciences and Humanities); Peter Yaworsky (Aarhus University); Felix Riede (Aarhus University)*

**09:50 – 10:10** 70. Understanding the spatiotemporal variation in Neanderthal hunting decisions across Western Eurasia 200ka to 50ka ago  
*Peter Yaworsky (University of Copenhagen); Konstantinos Dardavesis (University of Copenhagen); Trine Nielsen (Moesgaard Museum)*

**10:10 – 10:30** 24. The ROAD to palaeo-synanthropy in Late Pleistocene Europe  
*Shumon Hussain (University of Cologne); Chris Baumann (University of Tübingen)*

**10:30 – 11:00** Coffee break

**11:00 – 11:20** 228. A review of diverse computational methods applied to the ROCEEH Out of Africa Database (ROAD)

*Christian Sommer (Heidelberg Academy of Sciences and Humanities / Uni Tübingen); Angela Bruch\*; Nicholas J. Conard\*; Miriam Haidle\*; Christine Hertler\*; Volker Hochschild\*; Zara Kanaeva\*; Jesper Borre Pedersen\*; Friedemann Schrenk\*; Andrew W. Kandel\**

*\*Heidelberg Academy of Sciences and Humanities*

**11:20 – 11:30** Discussion

## 24. The ROAD to palaeo-synanthropy in Late Pleistocene Europe

*Shumon Hussain (University of Cologne)*

*Chris Baumann (University of Tübingen)*

Millennial-scale dynamics in species composition and processes of ecosystem assembly are long-standing interests in palaeo-ecology and Pleistocene archaeology and we here leverage the ROAD database to trace macro-evolutionary faunal trends across the Late Pleistocene archaeological record, roughly between MIS 6 and the end of MIS 3. This analysis is motivated by ecological and multispecies theorizing highlighting the often underestimated role and function of scavengers—both facultative and obligatory—in broader ecosystem processes as well as recent recalibrations of niche theory emphasizing interspecific niche construction and cross-species facilitation as potent drivers of long-term ecosystem change. We articulate these theoretical developments with recent evidence on anthropogenic “faunal filtering” in the deep past and the growing realization that ecosystem assembly was frequently mediated by opportunities for other species created by different human ways of inhabiting and using the landscape. Attention to and avoidance of the evolving human niche may therefore supply presently underappreciated mechanisms of long-term faunal change. We test some of these ideas by compiling a faunal presence-absence dataset of scavenging species (including all carnivores who are considered to also be facultative scavengers) from ROAD and quantitatively assess occurrence frequencies and patterns of co-association over time on a pan-European scale. By focusing in particular on the “palaeo-synanthropy hypothesis” the authors have developed in some of their earlier work—the tendency of some members of a species to orient their behaviour towards human neighbourhoods, especially the food-getting affordances provided by them—we show that such a theoretically-informed and data-driven approach can proffer new perspectives for Pleistocene archaeology and palaeo-ecology alike. Our results reveal a notable trade-off between the promotion of smaller bodied, “early adopter”

species close to human habitation sites and the gradual reduction of larger-bodied, and often confrontational scavengers such as hyenas, leopards, and lions from increasingly human-dominated tasksapes. We suggest that this offers a somewhat alternative perspective on the gradual demise of carnivorous megafauna during the Late Pleistocene, pointing to the importance of human agency for interpreting larger patterns of faunal change at archaeological sites and drawing attention to the cultural dimensions of species co-existence, which are never neutral but have different positive and negative consequences for different species co-inhabiting past environments with humans.

## 59. Quantifying Landscape Learning: Integrating Archaeological and Environmental Models of Early Modern Human Dispersal in Western Eurasia

*Jesper Pedersen (Heidelberg Academy of Sciences and Humanities)*

*Peter Yaworsky (Aarhus University); Felix Riede (Aarhus University)*

Understanding why some early *Homo sapiens* dispersals into Western Eurasia failed while others succeeded remains central to debates on the Middle - Upper Palaeolithic transition. Early appearances, such as the Bachokirian and Lincombian-Ranisian-Jerzmanowician (LRJ), are now attributed to anatomically modern humans but show demographic fragility and limited cultural continuity. By contrast, the Proto- and Early Aurignacian represent the first widespread and enduring settlement. This study combines quantitative and theoretical approaches to examine how cultural learning and environmental familiarity shaped these divergent outcomes. Drawing on triple-inheritance theory, which recognises the transmission of genes, environments, and cultural-ecological knowledge, we apply the concept of landscape learning to evaluate how groups acquired and chronicled spatial and ecological knowledge during colonisation. Using harmonised data from the ROCEEH Out of Africa Database (ROAD), we develop a Landscape Familiarity Index

(LFI) that scores archaeological indicators of environmental knowledge - such as raw material transport, site function diversity, symbolic behaviour and spatial organisation - on an ordinal scale, enabling cross-cultural comparison. To integrate the ecological dimension, we employ Species Distribution Modelling (SDM) to reconstruct potential bioclimatic niches based on climatic and topographic variables. Coupling LFI and SDM allows us to assess whether higher landscape familiarity correlates with stable or ecologically favourable zones, or whether it reflects cultural adaptation beyond environmental constraints. This integrated framework provides a scalable computational method for testing hypotheses on pioneer failure, adaptation, and landscape learning—demonstrating how coupling archaeological and environmental models can quantify the process by which unfamiliar environments becomes socially and cognitively mapped.

## 70. Understanding the spatiotemporal variation in Neanderthal hunting decisions across Western Eurasia 200ka to 50ka ago

*Peter Yaworsky (University of Copenhagen)*

*Konstantinos Dardavesis (University of Copenhagen)*

*Trine Nielsen (Moesgaard Museum)*

### Introduction

Neanderthals (*Homo neanderthalensis*) occupied regions of Eurasia for at least the last 350ka. The remnants of their subsistence patterns manifest in archaeological material, such as zooarchaeological faunal assemblages. These faunal assemblages represent a fragmented portion of the diet and indicate that Neanderthal diet varied both spatially and temporally. Understanding this variability has been challenging and is structured primarily by two components. First, the presence or absence of specific species in local ecologies. Second, behavioral decisions about which prey species to pursue.

Here, using faunal assemblages from dated archaeological contexts (n=180; Kandel et al. 2023) and Prey Choice Model from Behavioral Ecology (Stephens and Krebs 1986), we derive preliminary expectations about the relative abundances of species within zooarchaeological contexts as a function of their profitability within a Prey Choice framework. These preliminary results represent the first steps in estimating past ecological settings to test a series of hypotheses about its structuring of human hunting decisions and the impacts of climate and human hunting.

### Methods:

Using existing species lists (Pushkina and Raia 2008) and zooarchaeological data derived from the Role of Culture in Early Expansions of Humans – Out of Africa (ROAD; Kandel et al. 2023) we identify the diversity of species present within Western Eurasia 200ka to 20ka ago. Next, we deduce which species were most important for achieving the subsistence needs of prehistoric foragers using Prey Choice Model. Each species is unique in that they have different subsistence payoffs, like calories, protein, and fat, but then also non-subsistence payoffs, like fur, bone, and cultural uses. Accompanying these payoffs are species specific costs, like pursuit, butchering, and cooking, which can change relative to available tool technology. Given that human foragers are sensitive to hunger with only a limited number of hours in each day to meet subsistence needs, we should expect foragers to be selective of what food resources they pursue. Building on ethnographic observations and anthropological archaeology, we can quantify subsistence return rates (payoffs/time costs) to estimate relative ranks of prey species to identify species important for subsistence needs.

Building on this logic, we expect hunters to:

- I. Have a narrower diet focused on high-ranked prey species, when high-ranked prey species are abundant.
- II. III. Incorporate lower-ranked prey species in rank order as the prevalence of high-ranked prey species decline.



Always pursue high-ranked prey species upon encounter, regardless of their abundance, resulting in their abundance in the zooarchaeological record acting as a measure of prevalence in the past.

After identifying target species, the zooarchaeological data derived from ROAD is filtered to include only archaeological contexts with radiometric dates between 200ka and 20ka ago. Then, we visualize the composition of the zooarchaeological record with the expectation that the higher ranked prey species will tend to dominate assemblages, and that when these species decline, that lower ranked prey species will be added in rank-order. Next, we use a spatiotemporal species distribution model constructed using observations derived from ancient environmental DNA, fossil data, and modern observations and 1000-year resolution paleoclimate data to estimate habitat suitability for reindeer. To test hypothesis three, we use a quasibinomial generalized linear model – a form of logistic regression – to test whether habitat suitability at archaeological sites can predict the relative abundance of the highest ranked prey species, reindeer (*Rangifer tarandus*), while controlling for each assemblage's total NISP.

## Results

Preliminary results indicate that:

- Genera of high ranked prey species (i.e., reindeer, boar, fallow deer, red deer) generally dominate zooarchaeological assemblages (Figure 1a).
- When genera of high ranked prey species dominate the zooarchaeological record, medium, and low ranked species' genera are rare (Figure 1b), suggesting a narrower diet breadth.
- Estimated habitat suitability for reindeer strongly predicts the proportion of reindeer found within zooarchaeological assemblages (Figure 1c).

On average, high ranked prey species (i.e., reindeer [18.5%], boar [4.6%], fallow deer [6.6%], and red deer [18.9%]) make up 48.6% of assemblages (Figure 1a). We can see shifts in the general composition of zooarchaeological assemblages through time, which could be driven by shifts in the abundance

of high ranked prey species (Figure 1b). We find a strong positive relationship ( $\beta = 23.7$ ;  $p < 0.001$ ) between the estimated habitat suitability of reindeer at archaeological sites and their zooarchaeological abundance (Figure 1c).

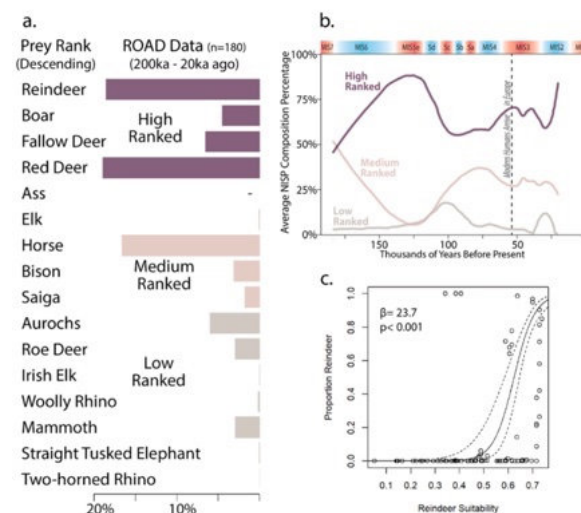


Figure 1: Panel a illustrates the prey rank of each species along with the average composition of the zooarchaeological record. Panel b shows how the change in composition of high, medium, and low ranked prey species through time. Panel c shows the model results illustrating the strong positive relationship between estimated habitat suitability for reindeer at archaeological sites and their abundance in the zooarchaeological record.

## Discussion

The results support the original hypotheses suggesting that hunting decisions are primarily structured by the relative abundance of high ranked prey species, like reindeer, boar, fallow deer, and red deer, to lower ranked prey species. High ranked prey species have the highest estimated post encounter

return rates. When these species decline in abundance, either as a result of climate-driven habitat shifts or human-induced population decline, Neanderthal diet breadth expands to include medium and low ranked prey species. Our test of hypothesis three suggests that zooarchaeological abundances of reindeer were primarily a product of climate-driven habitat shifts. The results have the potential to explain the spatial and temporal variation present within Neanderthal zooarchaeological assemblages. While these initial results support our hypotheses, they are not conclusive and additional analyses are needed. Critically, we need a method for identifying whether the spatiotemporal variation in zooarchaeological assemblages is a result of differences in the composition of prey species within specific ecological settings. To do this, the next step is to construct spatiotemporal species distribution models to estimate the paleobiogeography of the remaining target species, and test whether diet shifts correspond to climate-driven habitat shifts or human-induced hunting pressure. In doing so, we can better understand human foraging decisions and thus variation within the zooarchaeological record, allowing us to pursue questions pertaining to differences in hunting decisions related to behavioral differences between species and technological capabilities between cultures and through time, and better understand the role of humans in specific Pleistocene extinction events.

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## 84. Modelling Early Hominin Habitat Suitability in Eurasia: Integrating GIS and Machine Learning Approaches

*Ana Belén Galán López (CNRS UMR 7194 HNHP, National Museum of Natural History)*

*Carolina Cucart-Mora (CNRS UMR 7194 HNHP, National Museum of Natural History)*

*Christine Hertler (ROCEEH Research Center, Senckenberg Research Institute)*

*Marie-Hélène Moncel (CNRS UMR 7194 HNHP, National Museum of Natural History)*

During the first Out of Africa dispersal, Western Europe stayed at the limit of the human "Oikoumene" for almost 1 Ma. The earliest evidence of hominin diffusion out of Africa is dated to 2.1 Ma in Eurasia (Levant and China). Hominins reached the gateway of Europe, specifically the southern Caucasus, around 1.8 Ma, but the first human occupations of Western Europe are not observed until 1.2-1.4 Ma. Within our project (ERC Lateurope), we developed a computational approach to formalise and test different hypotheses while integrating available archaeological and climatic data.

One of these hypotheses argues that Europe was too inhospitable for early hominin populations to thrive. There is a consensus that early hominins were susceptible to climatic fluctuations. Paleoenvironmental reconstructions of the occupation contexts suggest that these took place during warm and wet interglacial or mild glacial periods. A recent study applying niche modelling (Margari et al. 2023) suggests that hominin habitat suitability dropped substantially in the Iberian Peninsula during the peak of MIS 34 terminal stadial event (1.12 Ma). The authors suggest that the worsening of climatic conditions would have led to the extinction of hominin populations. The Iberian

Peninsula, a region with an exceptional Early Pleistocene record, provides most of the European paleoanthropological record of that period and the most complete stratigraphic sequences. Particularly, at the Sierra de Atapuerca sites, we find the remains from Sima del Elefante (1.4 -1.1 Ma) (Atapuerca, Spain) ascribed to *Homo aff. erectus* (Huguet et al. 2025). In contrast, in Gran Dolina, *Homo antecessor* (ca. 0.9 Ma) was identified (Atapuerca, Spain), suggesting a population turnover took place around the same time as the documented drop in habitat suitability.

Therefore, it is of vital importance to understand the climatic context in which these early populations developed, as well as how this context may have affected them. To this end, within the modelling package of our project, we focus on the use of climate reconstructions to calculate changes in the habitat suitability of the territory for hominid populations between MIS 38 and MIS 13 (1.26 - 0.47 Ma). The first step of our workflow was to construct a dataset including all locations possibly ascribed to *Homo erectus sensu lato* between 2 Ma and 0.6 Ma in Europe, Asia and Africa. For this we used ROAD database as a baseline and main source of coordinates and completed the dataset with a thorough review of up-to-date literature. Currently, our dataset contains location data, chronological information, and the technological attribution and taxonomical identification of the recovered assemblages in a total of 290 locations. Climatic data is borrowed from Barreto et al. (2023). We apply Mahalanobis distance to reconstruct the changes in hominin habitat suitability. Specifically, we computed the habitat suitability for early European hominins as a cumulative probability with respect to the Mahalanobis distance between a set of climate input variables (Bio01, Bio04, Bio06, Bio12, NPP) and the same climate set of variables obtained for the hominin sites at ages. Subsequently, we constructed one envelope for each continent's population and projected it to Europe at different moments, i.e., beginning, terminal event, and end of MIS 34 (1.11-1.14 Ma) as well as terminal event of MIS 38 to 30 (1.26-1.03 Ma).

The first envelope suggests the Iberian Peninsula was habitable during MIS 34, meaning that considerable territory shows a habitat suitability index between 0.8 and 1. Looking more closely and projecting the envelope at

different times during MIS 34 (beginning, terminal and end), our model does not suggest drastic oscillations in habitat suitability as the one reconstructed at Margari et al. When only a subset of the presence data (i.e., archaeological sites from Europe, Asia or Africa) is used to construct the envelope, we observe a generalised decrease in habitat suitability. We observe an expected evolution of habitat suitability (decrease temperature – decrease HS) when we project the Asia and Europe envelopes during MIS 34 Europe. The projection of each continental subset onto Europe suggests that Early Pleistocene hominins adapted to very different climatic conditions. According to the results, the metapopulation seems to have been severely geographically isolated and adapted by continent.

Our results allow us to evaluate the potentialities of the tool to answer questions about regional and continental population dynamics. They suggest the potential to investigate the existence of climatically induced changes in corridors connecting the different areas and continents. If our results demonstrate that hominins adapted to markedly different ecological niches, this would suggest that early populations possessed—or developed—a considerable degree of behavioural plasticity, which enabled them first to disperse from Africa and subsequently to successfully colonise Asia and Europe. Our future work will focus on enhancing the model's complexity by incorporating additional geographical and geological variables such as paleo-shores, slope or water courses.

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## 155. Tracking change through time: habitat suitability changes for the first hominins of Europe

*Carolina Cucart-Mora (Museum National d'Histoire Naturelle)*

*Ana Belén Galán López (Museum National d'Histoire Naturelle)*

*Jan-Olaf Reschke (CNRS UMR 7194 HNHP, National Museum of Natural History)*

*Kamilla Lomborg (CNRS UMR 7194 HNHP, National Museum of Natural History)*

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### 193. An Overview of the ROAD Database and Its Application to the Study of Human Evolution

*Andrew Kandel (Heidelberg Academy of Sciences and Humanities)*

*Angela Bruch (Heidelberg Academy of Sciences and Humanities)*

*Nicholas Conard (Heidelberg Academy of Sciences and Humanities)*

*Miriam Haidle (Heidelberg Academy of Sciences and Humanities)*

*Christine Hertler (Heidelberg Academy of Sciences and Humanities)*

*Volker Hochschild (Heidelberg Academy of Sciences and Humanities)*

*Zara Kanaeva (Heidelberg Academy of Sciences and Humanities)*

*Jesper Borre Pedersen (Heidelberg Academy of Sciences and Humanities)*

*Friedemann Schrenk (Heidelberg Academy of Sciences and Humanities)*

*Christian Sommer (Heidelberg Academy of Sciences and Humanities)*

This contribution presents a progress update on a large-scale database aimed at the study of human evolution. Beginning in 2008, the research center “The Role of Culture in Early Expansions of Humans” (ROCEEH; [www.rocee.net](http://www.rocee.net)) designed, implemented and entered data into the ROCEEH Out of Africa Database (ROAD; <https://www.rocee.uni-tuebingen.de/roadweb/>). ROAD covers Africa and Eurasia between 3,000,000 and 20,000 years ago, combining data from the fields of archaeology, anthropology, paleontology, paleobotany, and paleogeography. ROCEEH makes this information freely accessible to all users online (Kandel et al. 2023). As of October 2025, ROAD contains over 2,600 localities and more than 28,000 assemblages. Data entry is controlled and reviewed to ensure a high quality of the content, which comes from more than 6,300 scientific publications written in over ten major languages. As the research center comes to an end in 2027, we summarize the major results of this endeavor.

Without logging in to the ROAD user interface, anyone can download a “ROAD Summary Data Sheet” containing an overview and further information about a selected locality. Video tutorials explain the basic principles of the database to novice users. The user-friendly interface of the entry web page, “ROAD Simple Search,” allows users to explore the contents of this expansive dataset and display the results on an interactive map. The application “Ask ROAD” provides an easy way for users to compose queries and retrieve data in a streamlined fashion. Finally, a new R Package called “roadDB” is now available for download on GitHub (<https://www.sommer-geo.com/roadDB/tutorial.html>) and is scheduled to be published on the Comprehensive R Archive Network (CRAN; <https://cran.r-project.org/>) by the end of 2025. With roadDB, a user familiar with R Studio can retrieve vast amounts of data stored in ROAD for further analysis. One final improvement is planned in 2026, the integration of ROAD into a large language model to facilitate querying using natural language.

Users can register to get their own log in credentials. This step allows users more access inside of ROAD. By logging in, users can view and filter data tables, compose queries tailored to their specifications using the “SQL Tool” and “SPARQL Tool”, visualize data in the “Map Module”, and use the “Time Slice Tool” for time series analysis. With the permission of the research center, users may enter their own data.

The data contained in ROAD can be used for advanced studies of human evolution. Depending on a researcher’s questions, data can be retrieved for further studies using, for example, agent-based modeling, network analysis, ecological and eco-cultural niche modeling, and a variety of statistical and machine learning tools. Data about climate and environment can be coupled with the archaeological record to observe changes over time in human behavior as it responds to changes in the landscape. As of October 2025, fifty-six articles published by ROAD users have incorporated data from ROAD into their research in various ways, and many more studies are underway. Results include research on the expansion of the human niche in Africa (Hallett et al.



2025), the effects of humans on carnivore guilds over time in Europe (Baumann et al. 2025), mapping cultural networks in the past (Sommer et al. 2023), the emergence of ochre use in Africa (Dapschaskas et al. 2022), and many more subjects.

ROCEEH is a partner of the ARIADNE Research Infrastructure (<https://portal.ariadne-infrastructure.eu/>), a European wide consortium with the mission of consolidating data and making it publicly accessible. The data contained in ROAD are aggregated in ARIADNE along with more than four million archaeological datasets covering a broader time depth and geographic scale than ROAD's purview. Further collaboration with the Coalition for Archaeological Synthesis (<https://www.archsynth.org/>) has helped ROAD follow the FAIR principles (<https://www.go-fair.org/fair-principles/>), ensuring that data are findable, accessible, interoperable, and reusable.

So, if you aren't already familiar with ROAD, we encourage you to take a look. We are offering a workshop on how to use ROAD at the CAA 2026 in Vienna, so feel free to register!

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## 228. A review of diverse computational methods applied to the ROCEEH Out of Africa Database (ROAD)

*Christian Sommer (Heidelberg Academy of Sciences and Humanities / Uni Tübingen)*

*Angela Bruch (Heidelberg Academy of Sciences and Humanities)*

*Nicholas J. Conard (Heidelberg Academy of Sciences and Humanities)*

*Miriam Haidle (Heidelberg Academy of Sciences and Humanities)*

*Christine Hertler (Heidelberg Academy of Sciences and Humanities)*

*Volker Hochschild (Heidelberg Academy of Sciences and Humanities)*

*Zara Kanaeva (Heidelberg Academy of Sciences and Humanities)*

*Jesper Borre Pedersen (Heidelberg Academy of Sciences and Humanities)*

*Friedemann Schrenk (Heidelberg Academy of Sciences and Humanities)*

*Andrew W. Kandel (Heidelberg Academy of Sciences and Humanities)*

The ROCEEH Out of Africa Database (ROAD, [https://www.roceeh.uni-tuebingen.de/roadweb/smarty\\_road\\_simple\\_search.php](https://www.roceeh.uni-tuebingen.de/roadweb/smarty_road_simple_search.php)) is an open-access platform containing a wealth of data on early human prehistory in Africa and Eurasia, spanning from 3,000,000 to 20,000 years ago. By combining

literature-sourced data on archaeology, anthropology, and paleoenvironmental studies into a structured data framework, it serves as a unique resource. ROAD offers various access options, including browser-based platforms, APIs, and statistical software packages, all under an open license (CC BY-SA 4.0), encouraging reuse by researchers.

In this paper, we provide a review of how ROAD has been used in conjunction with other datasets and computational methods to extract insights from the data. The review is based on publications that cite or mention the ROAD database, collected from both articles citing the ROAD introductory paper (Kandel et al. 2023) and mentions tracked via Google Scholar Alerts. The resulting list with over 55 publications is available at <https://www.zotero.org/groups/5497463/roceeh/library>.

The findings reveal that the majority of publications referencing ROAD are authored by external researchers, not directly involved with ROCEEH, highlighting the importance of open access in facilitating data reuse. Additionally, approximately half of the publications utilize various computational methods, demonstrating ROAD's value as an essential Big Data source.

This paper presents a diverse range of creative use cases, organized into six major categories: i) Time Series Analysis, ii) Ecological Niche Modeling, iii) Culture & Environment, iv) Culture & Physical Anthropology, v) Big Data and Machine Learning Approaches, and vi) Bachelor and Master Theses.

The goal of this presentation is to provide an overview of the scientific questions, complementary datasets, and analytical approaches applied to ROAD.

Kandel, A. W., Sommer, C., Kanaeva, Z., Bolus, M., Bruch, A. A., Groth, C., Haidle, M. N., Hertler, C., Heß, J., Malina, M., Märker, M., Hochschild, V., Mosbrugger, V., Schrenk, F., & Conard, N. J. (2023). The ROCEEH Out of Africa Database (ROAD): A large-scale research database serves as an indispensable tool for human evolutionary studies. PLOS ONE, 18(8), e0289513. <https://doi.org/10.1371/journal.pone.0289513>

## S27: Digital Communities: Collaborative Archaeologies, Shared Authority, and Community-Led Technologies

*Erica Maria Antoinette Van Vugt, University of Calgary*

*Zoe Cascadden Jassal, University of Calgary*

*Madisen Hvidberg, University of Calgary*

*Josephine Hagan, University of Otago*

**Location:** Hörsaal 02

**Session Format:** Standard

As digital tools and platforms become increasingly embedded in archaeological practice, they are reshaping not only how data is produced and disseminated, but also *who* gets to participate in those processes, and on what terms. At the same time, the decolonization of research paradigms and community-driven methodologies is expanding the field beyond traditional disciplinary boundaries. Community members, whether Indigenous Nations, local stewards, diaspora populations, or grassroots collectives, are claiming greater authority over their own heritage, memory, and material pasts. But while there is significant progress, much work remains to ensure that digital archaeological practices are not extractive, technocratic, or reproducing colonial patterns of control.

This session invites researchers, practitioners, and community partners engaging in **digital community archaeology** to share experiences, critical reflections, and visions for the future. We seek contributions that explore how digital technologies, such as GIS, 3D modelling, digital storytelling, data infrastructures, and online repositories, can support *ethical, collaborative, and community-centred research*. Of special interest are papers focused on work

with Indigenous and disenfranchised communities around the world, but we emphasize that “community” is not a singular or static category.

A key starting point for this session is the recognition that imperial frameworks have historically structured archaeological authority. As Silliman (2006) noted, archaeology often assumes that disciplinary expertise confers the sole right to interpret and control the material past, particularly with Indigenous belongings, sites, and narratives. This authority, grounded in Western academic training, often ignores or devalues other ways of knowing, especially those rooted in cultural, ancestral, or lived experience. In response, Indigenous archaeologies emerged to assert that Indigenous peoples have both the right and the knowledge to interpret and care for their own histories, lands, and cultural heritage (see Haakanson 2010; Simons et al. 2021; Supernant 2018; Yellowhorn 2006 for example).

Indigenous archaeology is research conducted *with, for, and by* Indigenous people (Atalay 2006:283). It recognizes Indigenous ownership over land, heritage, and representation, and it prioritizes multivocality, relationality, and the incorporation of Indigenous worldviews (Lyons 2016; Sillar 2013). Digital tools can amplify these goals when used in respectful, community-guided ways, but they can also risk flattening or misrepresenting Indigenous perspectives if deployed without care.

Community archaeology overlaps with, but is not synonymous with, Indigenous archaeology. Typically defined as research-driven or led by the community, sometimes referred to as “archaeology from below” or “grassroots archaeology” (Marshall 2002; Londoño 2021). While community archaeology shares approaches similar to those in Indigenous-led work, its epistemological grounding may differ, particularly when the community in question is not Indigenous. Methods such as co-creation, shared authority, and transparent communication must be attuned to the specific histories, politics, and aspirations of each community (Lassiter 2005).

Decolonizing archaeology intersects with both, while maintaining its own focus: the critical interrogation of archaeology’s entanglement with colonialism, modernity, and systemic inequity (Londoño 2021). However, it is not a single set of methods or a checklist—it is an ongoing political and relational

commitment (Quinless 2022; Wilson 2008). When digital methods are folded into decolonizing work, questions of infrastructure, access, representation, and data sovereignty become especially urgent.

This session offers space to reflect on these intersecting frameworks through the lens of digital practice. How can digital tools be made to serve community needs, rather than institutional ones? What tensions arise when integrating digital platforms with non-Western knowledge systems? How are authority, authorship, and access negotiated in collaborative digital projects? And what new forms of connection, resistance, or care might emerge when communities use digital technologies to tell their own stories?

We particularly welcome contributions that address:

- Community-led or co-designed digital heritage projects
- Indigenous or grassroots uses of digital technology in heritage or research contexts
- Collaborative mapping, modelling, or digital storytelling
- Ethics of access, data sovereignty, and long-term stewardship
- Digital return, repatriation, and re-connection with heritage
- Pedagogies and training models for community-engaged digital archaeology
- Theoretical reflections on authority, knowledge production, and decolonization

Institutional and structural challenges to doing this work sustainably

This session aims to foster dialogue across regions, research traditions, and community contexts. It is open to scholars, students, community members, and practitioners from any disciplinary background. Our goal is to bring together diverse voices and experiences that speak to the potential and the complexity of building *digital communities* in archaeology.

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|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>14:50 – 15:00</b> | <i>Introduction</i>                                                                                                                                                                                                     |
| <b>15:00 – 15:20</b> | 2. Virtual Lightbox: Computer Generated Conservation of Stained Glass<br><i>Kasi Zoldoske (University of York)</i>                                                                                                      |
| <b>15:20 – 15:40</b> | 11. Digital Preservation of Historical Archives: A Case Study of the Provincial Assembly of Khyber Pakhtunkhwa, Pakistan<br><i>Niaz Gul (KP Assembly Secretariate)</i>                                                  |
| <b>15:40 – 16:00</b> | 133. The Jolly Roger showed the way: A decentralised data repository using torrent and p2p technology<br><i>Juan Palomeque-Gonzalez (IDEA- Madrid)</i>                                                                  |
| <b>16:00 – 16:30</b> | Coffee break                                                                                                                                                                                                            |
| <b>16:30 – 16:50</b> | 182. Training small-data AI through community-driven annotation: towards Indigenous governance in archaeological computer vision<br><i>Benedict Dyson (Griffith University); Andrea Jalandoni (Griffith University)</i> |

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| <b>16:50 –<br/>17:10</b> | 262. Connecting Communities through Archaeological Prospection: Ten Years of the LoCATE Partnership<br><i>Kate Welham (Bournemouth University); Mike Gill (Bournemouth University); Hilde van der Heul (New Forest National Park Authority)</i>                |
| <b>17:10 –<br/>17:30</b> | 174. Digital Storytelling as an Approach to Dissonant Heritage Landscapes<br><i>Zoe Cascadden-Jassal (University of Calgary); Peter Dawson (University of Calgary)</i>                                                                                         |
| <b>17:30 –<br/>17:50</b> | 19. Digitally Grounded: Digital Heritage, Colonial Possession, and Relational Practices for Alberta Heritage Landscapes<br><i>Erica Van Vugt (University of Calgary); Peter Dawson (University of Calgary); Lindsay Amundsen-Meyer (University of Calgary)</i> |
| <b>17:50 –<br/>18:10</b> | 320. Documentation and Dialogue: Reflections on Eight Years of Digital Heritage Work with Indian Residential School Sites in Alberta<br><i>Madisen Hvidberg (University of Calgary); Peter Dawson (University of Calgary)</i>                                  |
| <b>18:10 –<br/>18:30</b> | 292. Shared Memories, Shared Maps: Co-creating Digital Archaeologies at Campo 65 (Altamura, Italy)<br><i>Daniele Mittica (University of Bari "Aldo Moro")</i>                                                                                                  |

## 2. Virtual Lightbox: Computer Generated Conservation of Stained Glass

*Kasi Zoldoske (University of York)*

This paper addresses the need for modern alternatives for the long-term preservation of stained glass, a field facing challenges from its fragile material and a professional hesitation to embrace new technologies (Myhre, 2024). While 3D modeling is an established tool within archaeology for recording and preserving artifacts, its application in stained glass conservation has been limited, and information regarding photogrammetry for this purpose is scarce. This research bridges this gap by exploring the use and accessibility of digital technologies, specifically photogrammetry, to create high-resolution 3D models of stained glass. The main argument posits that these digital models can effectively complement traditional physical preservation by creating comprehensive documentation that captures depth and details, such as cracks and corrosion, that are often missed in conventional 2D photography.

The projects demonstrate that both simplified and photogrammetry-based models can be used to simulate and study the effects of changes on the material and serve as accessible educational tools. The findings provide a practical framework for applying computer applications and quantitative methods in cultural heritage fields like archaeology (Bracqa, 2019; Ioannides, 2014). Ultimately, this work challenges the "barrier of distrust" (Yakel, 2024) toward new technology within the stained glass community and serves as a foundational step toward proving the utility of digital preservation as a means to ensure that knowledge of this endangered craft is not forgotten.

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## 11. Digital Preservation of Historical Archives: A Case Study of the Provincial Assembly of Khyber Pakhtunkhwa, Pakistan

*Niaz Gul (KP Assembly Secretariate)*

This study presents a comprehensive digitalization initiative of the Provincial Assembly of Khyber Pakhtunkhwa, Pakistan, preserving historical legislative documents from 1947 to 2025. Leveraging digital technologies, constitutional records, bills, and acts are transformed into accessible digital formats, ensuring long-term preservation and enhanced research opportunities. A key milestone was the passage of the historic Antiquity Act of Khyber Pakhtunkhwa, which empowers the archaeology department to independently preserve cultural heritage and combat antiquities smuggling within the province. This legislative framework has strengthened the department's

authority to protect and conserve archaeological sites and artifacts. Furthermore, a Legislative Support Library was established on both digital and manual platforms, providing lawmakers with comprehensive research support and informed decision-making capabilities. A dedicated digital museum and database offer stakeholders seamless access to legislative history, including records of members and speakers (1947-2025). This project underscores the significance of digital preservation in safeguarding cultural and institutional heritage, promoting transparency, and facilitating research.

**Keywords:** Digital preservation, legislative archives, cultural heritage, Khyber Pakhtunkhwa Provincial Assembly, Antiquity Act, Legislative Support Library.

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Provincial Assembly of Khyber Pakhtunkhwa. Legislative Support Library

## 19. Digitally Grounded: Digital Heritage, Colonial Possession, and Relational Practices for Alberta Heritage Landscapes

*Erica Van Vugt (University of Calgary)*

*Peter Dawson (University of Calgary)*

*Lindsay Amundsen-Meyer (University of Calgary)*



Alberta's built heritage is increasingly at risk due to age, environmental stress, and limited preservation capacity. Many of these structures, including grain elevators, vernacular frame houses, and fur trade posts, reflect the layered histories of settlement, adaptation, and displacement across the prairie landscape (Lea 1985). Yet, their documentation has long been constrained by a compliance-oriented system that satisfies regulatory minimums while overlooking the cultural meanings, experiential dimensions, and community relationships that give these places significance (Atalay 2006; Dawson et al. 2024). This paper presents Terrestrial Laser Scanning (TLS) and drone photogrammetry as tools that go beyond measurement, serving as instruments of accountability, memory, and relational care. Based on fieldwork at The Leavings in southern Alberta's Willow Creek region, the research shows how digital methods can provide both technical accuracy and relational landscape practices when guided by ethical frameworks.

Within Alberta's Cultural Resource Management (CRM) sector, heritage documentation has traditionally depended on the Heritage Survey Site Form (HSe-form). These forms record architectural features, structural conditions, and historical associations but seldom address broader concerns of authenticity, integrity, or commemorative significance (Parks Canada 2010). Such limited approaches risk turning heritage into a mere inventory rather than a dynamic, living record but by placing Alberta's documentation efforts within international frameworks such as UNESCO's focus on "outstanding universal value" and ICOMOS's emphasis on authenticity and community involvement, it is clear that Alberta's systems do not yet align with global standards or Indigenous and local perspectives on stewardship (Hvidberg 2020; Parks Canada Agency 2008; UNESCO). Without digital documentation and collaboration, Alberta's heritage records remain susceptible to both physical deterioration and epistemic loss.

In response, this project investigates TLS as a non-invasive, reproducible, and participatory method for documenting endangered heritage due to TLS allowing for the creation of highly accurate digital twins that support long-term monitoring and enable shared interpretation across disciplinary and community contexts. Instead of viewing data collection as an extractive act, this

approach treats digital recording as a collaborative intervention, a process that values relational engagement alongside technical precision. The Leavings covers a stretch of land that intersects public and private holdings, containing traces of both ancestral and colonial occupation. Physical and oral evidence document its long history of use by the Niitsitapi (Blackfoot), whose trail systems, cairns, and lithic scatters reveal patterns of movement and gathering. Later, the site became part of Oxley Ranch, a venture driven by the ambitions of Alexander Stavely Hill and managed by John Craig under Crown lease (Evans 1983). From 1884 to 1904, the North-West Mounted Police (NWMP) used the area as a staging post between Fort Macleod and Calgary, maintaining control along transportation routes during a period of increased settlement and surveillance, specifically, during the Riel Rebellion (Schelten-Cornish 1991; Voth and Loyer 2019). The NWMP barn, one of Alberta's oldest remaining outpost structures, anchors this study. Constructed with sandstone foundations and vertical wooden slats, its deterioration reflects environmental stress and historical neglect. The barn's carved inscriptions, dates, initials, and tool marks, serve as a record of human presence throughout the ages. These physical traces are crucial not only for heritage preservation but also for reinterpreting the site's layered stories of authority, labour, and land use. Fieldwork combined two scanning systems: the GeoSLAM Zeb Horizon, which uses Time-of-Flight and SLAM technologies for portable data collection, and the Z+F 5010x, a phase-shift scanner that produces high-density, millimetric point clouds (Evans 1983; Kersten and Lindstaedt 2022). Used together, these instruments offered both extensive coverage and architectural precision.

In this context, scanning was not only a method of measurement but also an act of witnessing. It embodied relationships among researchers, landowners, and descendant communities, while highlighting questions of authority: Who decides what is documented, who interprets it, and who benefits from its digital circulation?

Digital heritage goes beyond just digitization; it involves creating, managing, and sharing digital representations of cultural resources (Buragohain et al. 2024). In Alberta, where over 300 provincially designated sites exist, many

located in rural or private settings, these approaches can change how heritage is understood and preserved (HERMIS; Schaepe 2020). However, decolonizing digital practice requires more than just adopting technology, as Londoño (2021) and Atalay (2006) highlight; decolonization is an ongoing relational commitment rather than a mere checklist. In the context of the Leavings, this means understanding that digital models must be grounded in local and Indigenous epistemologies, that point clouds and meshes gain meaning only through the stories, languages, and protocols that surround them. They prompt reflection on the entwined histories of colonial infrastructure, Indigenous displacement, and regional identity, a complexity that purely technical documentation cannot fully convey (Schaepe 2020). The outcomes of this research point towards a pathway towards collaborative digital stewardship within Alberta's heritage sector. Such a framework would incorporate:

- Shared authority between CRM practitioners, Indigenous Nations, and local stakeholders in project design and interpretation.
- Ethical governance of digital data, ensuring informed consent, cultural protocols, and community access.
- Compatibility with provincial systems like HeRMIS through standardized metadata and preservation formats.
- Training and capacity building to foster digital literacy and autonomy among community participants.

Embedding these principles aligns Alberta's heritage practice with international standards while remaining sensitive to local relationships and responsibilities. In this way, TLS and photogrammetry serve not just as documentation tools but as mechanisms for redistributing heritage authority, changing who gets to participate in preserving the past and under what terms. Digital technologies have the potential to preserve Alberta's endangered heritage, but their true importance depends on how they are used. Ultimately, this work asserts that digital heritage in Alberta must move beyond mere compliance and towards co-creation, a practice that recognizes the interconnectedness of people, place, and the technologies that preserve their memories.

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### 133. The Jolly Roger showed the way: A decentralised data repository using torrent and p2p technology

*Juan Palomeque-Gonzalez (IDEA- Madrid)*

#### Introduction

Archaeological research increasingly depends on digital repositories to preserve and disseminate data. However, these repositories often rely on centralised infrastructures that are constrained by funding cycles, institutional mandates, and limited interoperability, producing biases and economic conditions that can affect how archaeological knowledge is produced and maintained (Huggett, 2023). This project explores a decentralised alternative for archaeological data storage and sharing, using peer-to-peer (P2P) and torrent-based technologies to distribute datasets across a network of contributors, reducing long-term dependence on project funding and institutional maintenance for data preservation and sharing.

#### Methods and Materials

The project investigates the feasibility of a decentralised data repository built on open P2P protocols. Each dataset is encapsulated as a self-contained package that includes the data, metadata, and origin of information, distributed via torrent or magnet links.

For the purposes of this project, a variety of data formats were taken into account, not only tabular data, but other types of structured and unstructured archaeological data, such as images or written documents. For each package, a cryptographic hash is calculated, to ensure data integrity and traceability.

A federated index was created, a public registry of torrents with persistent identifiers, said cryptographic hash, the compiled metadata and other citation information. The index allows users to search and compile the links for the data packages they are interested in.

The global design of the system is aligned with FAIR (Findable, Accessible, Interoperable, Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, Ethics) principles.

A working prototype is being developed in Python, using existing open-source tools such as libtorrent, to generate the discussed data packages, compiling archaeological datasets with free distribution licenses.

#### Results

Preliminary trials show that torrent-based data replication can be effectively used for data sharing, reducing the dependency on centralised servers only for updated versions of the federate index. Data and metadata integrity and traceability can be checked through hash checking and the use of universal unique identifiers.

#### Discussion

A decentralised repository could transform digital archaeological practice by distributing both storage and stewardship across the research community. The approach aligns with recent reflections on the sociotechnical nature of digital infrastructures (Huggett 2024) and ongoing calls for resilience, openness, and equity in archaeological data management (Taylor 2023). Beyond technical implementation, the project engages with questions of governance, trust, and long-term preservation — essential elements if P2P infrastructures are to become viable complements to established archives.

#### Conclusion and Future Work

This work introduces the conceptual and technical framework of a decentralised archaeological data repository using torrent and P2P technologies. Future work would include public testing, repository federation, and the definition of community protocols for dataset standardisation, validation and citation. By integrating open and distributed technologies, this approach demonstrates the potential for a resilient, equitable, and community-governed ecosystem for archaeological data management.

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## 174. Digital Storytelling as an Approach to Dissonant Heritage Landscapes

*Zoe Cascadden-Jassal (University of Calgary)*

*Peter Dawson (University of Calgary)*

Digital storytelling has proven to be an adaptable, useful tool for museums and researchers in disseminating site information and engaging the public in collections within archaeology. Digital storytelling brings narratives to an audience using digital technology and multimedia, which has expanded the possibilities of knowledge dissemination in the discipline (Earley-Spadoni 2017). This method of storytelling has been beneficial for community engagement, both in the creation of and interaction with a narrative, as well as illustrating multiple stories related to a historic object or site (for example, Bonacini et al. 2018; Katifori et al. 2014). This paper strives to explore how digital storytelling can be used for sharing narratives related to dissonant heritage landscapes using the ESRI StoryMap for the Old Sun Residential School developed as part of the Digitally Preserving Former Indian Residential Schools in Alberta project as an example.

Despite increased research into dissonant heritage sites, there is still limited work completed related to dissonant heritage landscapes, especially for landscapes outside of war-related contexts. Dissonant heritage has complex meanings and generally has had limited representation in public spheres due to negative connotations (Kačerauskas 2023). In a Canadian context, dissonant heritage has been largely overlooked. With the release of the Truth and Reconciliation Commission of Canada's Calls to Action, a list of 94 recommendations for addressing the legacy of the Indian Residential School system and reconciliation, in 2015 as well as the 2021 discovery of unmarked graves at the former Kamloops Indian Residential School, a greater public awareness of the dark side of Canada's history was generated but there are still major steps needed to increase education related to the dissonant legacy of the Residential School system and its impact on contemporary Indigenous communities across Canada. The Residential School system in Canada was a method of cultural genocide first introduced in Canada in 1844. It aimed to "civilize" First Nations to fit into the Euro-Canadian settler society (IAPOC 2021). These schools functioned through forcibly removing children from their families and subsequently stripping them of their language, cultural identity, and were often abused. Residential schools operated for over a century in Canada, with more than 150,000 Indigenous children having attended 140 schools by 1997 when the last Residential school closed (IAPOC 2021).

The Digitally Preserving Former Indian Residential Schools in Alberta project was developed as a way for communities to commemorate their residential school experiences. Based in the framework of Research as Service, this project is led by partner Indigenous organizations including Old Sun Community College, Poundmaker's Lodge Treatment Centre, and University nuhelot'ine thaiyots'i nistameyimâkanak Blue Quills. Our team has facilitated the creation of digital twins of the remaining residential school buildings for commemoration on our digital archive and a collection of survivor stories ([irs.preserve.ucalgary.ca](https://irs.preserve.ucalgary.ca)). The second phase of this project has commenced, which includes capturing and commemorating the schoolgrounds at the Residential School sites and is the focus of this paper.

Landscapes are important components to heritage, as they are often deeply intertwined with intangible aspects of heritage. Landscapes provide a 'sense of place' and can act as an embodiment of shared rememberings by a group of people (White III & Bethke 2019). In the case of Residential schools, it has been shown that survivors have complex relationships with the schoolgrounds and gardens that were part of their experiences. The landscape is an important aspect of Residential School heritage to commemorate as it has been shaped by the school policies as well as the experiences of students (White III & Bethke 2019). It is for this reason that digital storytelling is suited to presenting the narrative of the schoolgrounds, as it provides a way to relocate memories and represent the multiple narratives related to the experience of Residential School.

Earley-Spadoni (2017) suggests that digital storytelling allows the creator to illustrate multiple perspectives, particularly in the development of a deep map, wherein a multi-layered digital map is created that allows for the representation of intangible elements to be incorporated into an otherwise static map. The intangible aspect of dissonant spaces can be difficult to present in traditional forms, especially when associated with a landscape, but by linking the memories spatially, there is an opportunity to embed knowledge through digital storytelling and deep mapping which in turn can create deeper connections amongst audiences through spatially linked information (Earley-Spadoni 2017). ESRI StoryMaps was determined to be a useful tool in creating an interactive platform for memories of survivors to be re-linked to the landscape. For this project, memory-maps based on survivor stories have been created and highlight important locations that are now gone through digitally marking them on the current landscape. This allows the user to critically think about how the landscape is shaped by history and understand the relationship between the schoolground and student experiences at Old Sun as they navigate through the StoryMap. As the program allows for the inclusion of multimedia, Archival imagery, aerial images, documents, and video were included to increase the breadth of information

related to the Old Sun schoolgrounds that the user could view and interact with.

The StoryMap presented in this paper is an example of how digital storytelling can manifest for dissonant heritage landscapes. It provides a way to bring together many resources and link them through their connection to the landscape, creating a deeper understanding of the complex narratives associated with Residential schoolgrounds (White III & Bethke 2019). This has the potential to be applied at other dissonant heritage landscape sites, creating more options for presenting difficult stories. Creativity and collaboration in the development of new ways of conveying information, such as through the diverse potentials of digital storytelling, establishes a way for engaging and educating the public about topics that may be inaccessible without a digital platform or that may be avoided in traditional forms of communication (Perry et al. 2025). Additionally, through software such as ESRI ArcGIS StoryMaps, intangible aspects of history can be re-embedded into landscapes digitally, allowing both users and local communities to have a greater connection with that place.

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## 182. Training small-data AI through community-driven annotation: towards Indigenous governance in archaeological computer vision

*Benedict Dyson (Griffith University)*

*Andrea Jalandoni (Griffith University)*

Rock art, particularly when exposed to extreme weather events, requires rapid and scalable documentation methods to support long-term monitoring, analysis and engagement. Previous research has shown that computer vision is a viable method for identifying and classifying rock art, however, most have highlighted the limited availability of labelled data. We suggest that domain-specific augmentations make small, community driven datasets viable for AI model training, suitable for production.

Injalak Hill, Northern Territory, Australia boasts highly dense rock art from tens of thousands of years ago to the present day. Recent fieldwork suggests there are likely upwards of 10,000 visible motifs present on the hill and annotating each of them individually would be a very time-intensive task. The training of a computer vision model was explored to reduce the workload of this task. Training data were derived from annotations drawn on an iPad with a stylus by Indigenous artist Joey Nganjmirra. These were processed into polygons and projected onto photogrammetry-derived 3D models. Annotations could then be propagated to all images in the photogrammetry datasets.

The philosophy behind the training was focused on making the most of smaller training datasets, with augmentations tuned to the domain of rock art, these included an enhanced copy paste augmentation, specifically tuned to simulate motif degradation. On an initial training run we found that these augmentations increased our mAP score from 14.80 to 27.03 (183%) and AP75 scores from 5.52 to 32.26 (584%). By copy and pasting motifs across images, it is possible to ensure the model learns true representations of the motifs rather than underlying noise that would typically affect small datasets.



As future projects become increasingly reliant on these outputs, we minimise reliance on human interpretation. Machine-generated data has the potential to degrade human interpretive authority. However, we suggest this could be mitigated through appropriate data structures. We distinguish Aboriginal, archaeological, and machine-generated annotations, allowing analyses to weight trusted sources appropriately.

Through combining Indigenous knowledge and cutting-edge technology, we have demonstrated that effective computer vision models can be trained and utilised for identifying rock art motifs. Automated methods can contribute to a sustainable future for heritage management, however, there are ethical, methodological and theoretical implications, particularly surrounding interpretive authority. Transparent, community-informed AI pipelines can enhance both the efficiency and accountability of heritage documentation. This framework of provenance-aware annotations could become a model for future AI governance in archaeology.

## 262. Connecting Communities through Archaeological Prospection: Ten Years of the LoCATE Partnership

*Kate Welham (Bournemouth University)*

*Mike Gill (Bournemouth University)*

*Hilde van der Heul (New Forest National Park Authority)*

### Introduction

This paper is presented by researchers, practitioners, and community partners who are engaged in the co-creation of research through an innovative community archaeology partnership based on archaeological prospection techniques. LoCATE (Local Community Archaeological Training and Equipment) is a project based in the UK that brings together a) archaeological and heritage societies and community groups from across Dorset and Hampshire, with b) archaeologists at Bournemouth University and c) heritage professionals at the New Forest National Park Authority (NFNPA). This collaboration

was instigated in 2015 and provides access, training, and support for the use of advanced survey equipment that can otherwise be hard for partners to access.

In this paper, we share the experiences gained from a decade of successfully running LoCATE. We critically reflect on approaches that can ensure the sustainability of such projects, training models for community-engaged digital archaeology, and models that seek to support and empower community generated, and led, research.

### Co-design and a Partnership Approach

LoCATE was co-designed to be a digital heritage project that supported the existing work that all partners were already involved in but aimed to extend this in a mutually beneficial way. The University was looking for sustainable ways to engage with its local community, share knowledge and expertise, and create benefit for the local region. The NFNPA was seeking ways to expand its existing well-established volunteer groups and broaden the offer to these in terms of digital skills to support recording of the internationally significant heritage in the National Park. The local community groups were keen to address questions about their local heritage assets alongside access to specialist equipment and expertise to expand their capacity to undertake place-based research.

To create a sustainable project and long-term partnership, LoCATE was deliberately set up to maximise the existing resource in each partner organisation. Importantly, this does not rely on additional funds to run, as this is often a common point of failure in projects of this type. A loan agreement between the University and the NFNPA enables older, but serviceable geophysical equipment that is not being used regularly for teaching and other activities to be located within the NFNPA headquarters. This then allows this equipment to be managed by the NFNPA who have the existing front facing loan and management system via their volunteer hub. Any servicing/maintenance

costs are therefore covered by the University, as they still own the equipment, reducing the risk of equipment failures.

To ensure shared authority the partnership members draw on their different expertise and work together to give members free training on techniques. LoCATE members also sign up to a code of responsible survey and data sharing. Open data is a core value, and members are supported to use open access materials and software. Inter-partner support and the cascade of knowledge is fostered through a variety of means including shared prospection activities, and project social media channels.

#### Outcomes

Over the past decade, LoCATE has engaged over 600 people across Dorset and Hampshire. It has expanded its equipment base including accessed community funds to enable digital geospatial recording for the geophysical surveys. It has resulted in new knowledge and understanding of a wide variety of sites from prehistoric monuments, including 22 Neolithic long barrows many of which were previously unknown, to extensive Romano-British sites in Hampshire and WW1 remains (Gill 2019a; 2019b).

LoCATE has consistently offered a model where members achieve their own research aims but also enable an improved understanding of the rich archaeological heritage of the region. This is an important factor as the historic environment of Dorset and Hampshire is internationally significant, but many sites remain poorly understood. Local communities are highly motivated to address this knowledge gap but lack access to specialist archaeological prospection and remote sensing knowledge and expertise that academic researchers have expertise in is often difficult to unlock within the constraints of modern academia.

#### Conclusions

LoCATE offers a model and an approach to partnership between researchers, practitioners, and local communities. The project has had multiple outcomes

including the empowerment of community, creating cultural impact and societal value, helped to protect and realise the region's heritage, and contributed to sustainable planning and development policies. It has created health and wellbeing impacts by empowering participants to conduct their own outdoor activities with a strong sense of purpose that bring their members together and reduce social isolation in what are often rural, ageing and isolated communities.

LoCATE provides a sustainable model for community engagement in archaeological prospection projects. The co-creation model has, to date, successfully mitigated the 'single point of failure' issues often associated with community archaeology projects of this type. In an era where the integration of digital techniques and data are central themes, it is perhaps timely to also consider the integration of people, and how we best work with a variety of different communities to create a shared understanding of our collective past.

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## 292. Shared Memories, Shared Maps: Co-creating Digital Archaeologies at Campo 65 (Altamura, Italy)

*Daniele Mittica (University of Bari "Aldo Moro")*

Campo 65, located in the countryside of Altamura (southern Italy), was built in 1940 to hold more than twelve thousand Allied soldiers as a prisoner-of-

war camp. After the war, it was used as a training center for Yugoslav partisans, a reception camp for Italian refugees from the Julian-Dalmatian area and former colonies in Libya in the 1950s, and finally for military training after its official closure in 1962, before being largely demolished between the 1980s and 1990s. Nowadays, only a dozen buildings are still standing, and the outlines of its internal structure are still clearly traceable on the terrain (De Felice 2021). This paper frames Campo 65 as a case study within the domain of contemporary archaeology, exploring how digital tools and participatory methods can document, interpret, and share the memory of this recent heritage in ways that engage both specialists and local communities. While GIS, photogrammetry, and 3D modelling enhance precision and accessibility, they also reshape participation and authority in archaeological practice. Drawing from previous experiences related to this site, this contribution aims to demonstrate how participatory digital practices can transform archaeological documentation into shared processes of knowledge production and civic engagement.

The first task was an extensive aerial photogrammetric survey carried out with a DJI Mavic 3 Enterprise RTK drone for about 31 hectares, supported by a GNSS antenna for ground markers. In parallel, the work made extensive use of historical sources such as, texts, project drawings, oral testimonies, aerial photographs (including U.S. reconnaissance images from September 2, 1943, taken before the Armistice), and several archival photos documenting later phases of the camp's life. These materials were georeferenced in GIS and integrated as informative layers within the QField project, enriching the spatial interpretation and supporting the reconstruction of historical transformations (Montagnetti and Guarino 2021).

This dataset then served as the basis for a customised QGIS and QField project used for mobile mapping: in this sense the team was hence able to place and record visible archaeological evidence in situ using a collaborative workflow.

This activity was extended further with an educational project where students from the Liceo Cagnazzi of Altamura used QField and iPhone LiDAR to carry out detailed surveys of selected architectural elements, in combination

with a digital storytelling approach for dissemination and communication purposes, in terms of co-creation and collaborative experience (Bollwerk 2015).

Although still in its development phase, the project has already laid important foundations in terms of its conceptual and methodological framework, identified in the definition of a flexible data architecture for the relationship among spatial, historical, and photographic records, and in the testing of collaborative workflows during field activities where shared data collection and interpretation proved feasible.

This can be conceived as a digital ecosystem that fosters ongoing collaboration and shared authority between archaeologists, students, and local communities. Further phases will incorporate other historical datasets and community-generated content to describe how digital infrastructures can work as relational artefacts in the transformation of the archaeological record into a multi-layered narrative of place and memory.

By framing digital documentation as both an analytical process and one of storytelling, the project invites consideration of the long cycles of occupation, reuse, and abandonment that have characterised the site.

This participatory approach also underlines some of the key challenges related to data ownership, representation, and sustainability. The collaboration with local stakeholders highlights that open access and community access do not necessarily coincide, and that participation is about finding a balance between transparency, responsibility, and mutual trust.

The Campo 65 project shows the potential of open technologies in enhancing the accessibility, interpretation, and public engagement with a contemporary site, allowing new ways for diverse audiences to experience and understand the site's history.

This perspective, framed as a "digital archaeology of care", privileges relationships over data extraction and emphasizes sensitivity to emotional and historical contexts.

The co-creation approach is central not only among archaeologists operating in the field but through a synergic dialogue with students, local communities, and other heritage stakeholders. Recognizing how digital tools shape both

narratives and participation, this project advances a reflective and socially engaged approach where maps and models are part of shared interpretive spaces reconnecting people, place, and memory.

Building on these reflections, the wider implications of this research extend beyond the methodological domain: this ongoing project shows how digital and participatory approaches can be a form of shared custodianship for sites of memory at a time when Europe faces renewed debates about identity, conflict, and collective remembrance.

Campo 65, one of the largest WWII POW camps in Italy, has been indeed selected as one of only eleven Italian sites to compete for the “European Heritage Label”; this nomination itself underscores its outstanding value as a place of shared European memory and resilience.

Furthermore this project, developed in partnership with the Municipality of Altamura and the local association “Associazione Campo 65”, thus contributes not only to the documentation of a local heritage site but to a wider dialogue on how digital and community-led technologies can support the preservation, understanding, and dissemination of our recent past. It is through this collaborative approach that the research underlines the responsibility of archaeology to create open, inclusive, and participatory pathways to heritage, as well as encouraging reflection on memory, identity, and the evolving meanings of the recent past and its material legacies in contemporary Europe.

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## 320. Documentation and Dialogue: Reflections on Eight Years of Digital Heritage Work with Indian Residential School Sites in Alberta

*Madisen Hvidberg (University of Calgary)*

*Peter Dawson (University of Calgary)*

Over the past decade, archaeologists and heritage scholars have increasingly turned to digital technologies as tools for collaboration, co-creation, and, in Canadian contexts, reconciliation. At the same time, decolonizing research paradigms have reshaped how we understand authority, knowledge production, and ethical responsibility in archaeological and heritage practice. This paper brings these digital and ethical currents together through a reflection on eight-years of participation on a project employing digital documentation methods at three former Indian Residential School (IRS) sites in Alberta.

Using terrestrial laser scanning (TLS) and drone-based photogrammetry, this project—now continuing into Phase 2 —seeks to document and preserve IRS sites as directed by Indigenous advisory groups as a means of addressing the legacy of social and emotional weight left by the IRS system. From the outset, the aim of this work was not simply to digitally record and research these structures, but to explore how such technologies could serve community-defined purposes—whether for remembrance, education, or healing. Grounded in community-based research practices this project evolved in close dialogue with Indigenous partners, operating at the intersection of digital, Indigenous, and decolonizing archaeologies (Atalay 2006; Lyons 2016; Londoño 2021). It asks how digital heritage practices—often framed as neutral or universal—might instead become relational, responsive, and locally meaningful. Building on Indigenous archaeologies’ call for research

conducted with, for, and by Indigenous peoples (Atalay 2008), it examines ways digital media can embody these principles through collaborative workflows, community review processes, and protocols for data governance and access.

Now, nearly eight years after initiating this work and finishing writing my dissertation, I reflect on the complexities of conducting decolonizing research as a non-community member. While digital tools provided new possibilities for preservation and dialogue, they also highlighted enduring asymmetries of power, access, and authorship. Working with Indigenous communities at sites of historical trauma required continuous negotiation of roles, responsibilities, and expectations—reminding me that decolonization is not a completed act, but an ongoing relational process. Digital heritage work is dynamic not only as a technical practice but as a space of ethical encounter where archaeologists must continually reassess their positionality and accountability. This presentation will consider both the successes and tensions of this long-term digital research collaboration and by situating these experiences within broader debates on community and decolonizing archaeologies, it will contribute to ongoing conversations about what it means to build truly digital communities in heritage research.

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## S32: Replay: Computational Heritage of Games

*Summer Courts, University of Reading (chair)*

*Walter Crist III, Leiden University (chair)*

*Tim Penn, University of Reading (chair)*

*Barbara Care, University of Lausanne (chair)*

*Branislav Kovar, Slovak Academy of Science*

*Dorina Moullou, Hellenic Ministry of Culture / Hellenic Open University*

**Location:** Hörsaal BIG

**Session Format:** Standard

Computational approaches are transforming the way we understand and preserve cultural heritage. One emerging—and presently underexplored—area is the application of Artificial Intelligence (AI) and other computational methods to traditional games. Traditional games—particularly board games—offer a unique window into the past, reflecting social norms, values, and behaviours that are at risk of being lost due to their intangible nature. The rules, playing contexts, and embodied practices often remain undocumented or only partially preserved.

Though existing studies (Crist et al. 2024; Browne 2023; Donkers et al. 2000) have made strong opening moves, the field is still in its early game. Much of the board remains unexplored, with significant potential for computational methods to advance our understanding). This session—organized by the COST Action (CA22145) Computational Techniques for Tabletop Games Heritage (“GameTable”)—aims to expand on the themes of our upcoming special issue in JOCCH (*Journal on Computing and Cultural Heritage*). This session will explore the reconstruction and preservation of traditional games, viewing them not merely as leisure activities but as rich cultural artifacts and historical narratives that are vital for a deeper understanding of human societies. By integrating perspectives from archaeology, artificial intelligence, and cultural studies, this session will allow us to “replay” the past and begin

writing the playbook for how computational methods can help illuminate the playability, strategies, and social functions of traditional board games.

### **Topics for Discussion:**

This session invites papers and presentations addressing a broad range of themes related to computational approaches to games heritage, including but not limited to:

**Computational reconstruction of traditional games:** Using methods such as procedural content generation, human-in-the-loop AI, and human-like AI to infer or rebuild game mechanics and rule sets.

**Machine learning for game identification:** Applying techniques such as text mining or gameplay metric analysis to identify, classify, or interpret traditional games.

**Simulating traditional games:** Developing digital implementations and/or tailored, explainable AI agents to simulate how games may have been played.

**Analysis of digitised traditional games:** Exploring gameplay data and strategy detection to better understand player behaviour and game design.

**Mathematical and statistical modelling:** Creating formal models of gameplay, game balance, or player strategies based on historical data.

**Computer vision applications:** Applying image analysis to recognize, reconstruct, or interpret physical components of games from archaeological or archival materials.

**3D modelling of game artifacts:** Generating accurate digital representations of historical gaming objects for research, preservation, or display.



**Educational and heritage engagement:** Exploring how reconstructed games can support education, public engagement, or digital storytelling in heritage contexts.

**Digital documentation of gaming materials:** Using computational tools to support the archaeological recording and interpretation of game-related artifacts.

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|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 11:40 – 12:00 | 375. LUDITECH: Integrating Tactile Sensing and Computational Modelling in the Archaeology of Ancient Board Games<br><i>Barbara Care (University of Fribourg); Theodora (Dorina) Moullou (Hellenic Open University)</i> |
| 12:00 – 12:20 | 114. Is Pente Grammai a playable game? Simulation as a third filter for rules reconstruction for historical games                                                                                                      |

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|-------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>James Goodman (Queen Mary University of London); Summer Courts (University of Reading); Timothy Penn (University of Reading)</i> |                                                                                                                                                                                                                                                                                                                                                        |
| 12:20 – 12:40                                                                                                                       | 110. Rolling the Roman Dice: Experiencing Ancient Chance with AI<br><i>Summer Courts (University of Reading ); James Goodman (Queen Mary University of London); Timothy Penn (University of Reading)</i>                                                                                                                                               |
| 12:40 – 13:00                                                                                                                       | 109. Ludus ex machina: Studying Ancient and Historical Games through Human-like AI Play Agents<br><i>Timothy Penn (University of Reading); James Goodman (Queen Mary University of London); Eric Piette (Université catholique de Louvain); Summer Courts (University of Reading ); Walter Crist (Leiden University); Alois Rautureau (ENS Rennes)</i> |

**109. Ludus ex machina: Studying Ancient and Historical Games through Human-like AI Play Agents**  
*Timothy Penn (University of Reading)*  
*James Goodman (Queen Mary University of London)*  
*Eric Piette (Université catholique de Louvain)*  
*Summer Courts (University of Reading)*  
*Walter Crist (Leiden University)*  
*Alois Rautureau (ENS Rennes)*

Artificial Intelligence (AI) research in games has traditionally pursued optimal, perfect play (Yannakakis and Togelius 2025), particularly in the field of Classical or Symbolic AI. This focus that fundamentally overlooks the cultural, emotional, and social dimensions that define why and how humans play both now and, in the past—and means when faced with archaeological evidence for boardgames we cannot yet answer basic questions such as “how did people play?” Meanwhile, historical and archaeological games research has emphasised the culturally embedded nature of human play, finding that most rules are social rather than formal (Stenros and Montola 2024).

Previous work has explored some possibilities of suboptimal play in relation to modern games such as backgammon and poker (Tesauro 1995; Moravčík et al. 2017) or through ‘game balancing’ in other research areas such as game design, which have drawn on procedural content generation approaches (e.g. Rupp 2025). However, this concept has not previously been applied to modelling of games in the past through Classical AI methods; existing modelling of ancient games does not account for humanlike play patterns, as AI agents are typically only conditioned to seek victory at all costs (as noted by Soemers et al. 2025, see e.g. Crist et al. 2024; Browne 2023; Donkers et al. 2000).

This project pioneers a new approach to bridge this gap between qualitative cultural archaeological and historical studies and quantitative execution, using the Roman boardgame *Ludus duodecim scriptorum*, an ancestor of modern backgammon (Schädler 1999), as a case study. We investigate what constitutes “humanlike play” in this historical context, seeking to answer: How can culturally specific, non-optimal behaviours be formalised into executable AI constraints to test reconstructed historical rulesets and aid in the interpretation of the archaeological record? By inverting the traditional AI pipeline, this work seeks to transform AI into a partner for cultural simulation, moving beyond simple optimality, as it has previously been employed in historical games studies.

The core method adapts standard game-tree search and reinforcement learning techniques - a core branch of Classical AI - within the Tabletop

Games Framework (TAG) (Gaina et al. 2020; Goodman et al. 2024) guided by archaeological and historical evidence: our ancient evidence consist of hundreds of references to play from Roman textual and iconographic sources, including the Loeb Classical Library and the Callisto database, which describe non-rational, social play strategies like deliberate loss and risk-taking on a gameboard type commonly found in the archaeological record across the Roman Empire (e.g. Talloen 2019; Schädler 2022). Our core aim is to cast new light on how these gameboards were used. We will translate these qualitative archaeological and historical insights into quantitative models by encoding them as modified, non-binary reward functions and customised Monte Carlo Tree Search (MCTS) heuristics. This approach contrasts with data-driven human simulation, as it uses the culturally rooted historical evidence itself as the objective function for the AI agent. The outcome is the first attempt to apply a suboptimal play framework to historical games.

This project aims to develop a formalised behavioural taxonomy of non-optimal Roman play traits and a Functional Proof-of-Concept Agent for *ludus duodecim scriptorum*. Simulation runs will compare the behaviour of an Optimal AI agent with the new Humanlike AI agent (n.b. this does not mean pitting these two agents against each other; we will run a range of matchups between different AI agents as part of the research design), generating quantifiable results that provide empirical opportunities to explore the implications of different types of non-optimal modelling when exploring ancient games. Our results will attempt to quantify the strategic viability of non-optimal social behaviours, such as the viability of a player deliberately losing to their partner (e.g., as suggested by Ovid, *Ars Amatoria*, II. 203-208) – as this project is ongoing, we will provide further exemplars of such behaviour at the CAA meeting. Our analysis is an attempt to produce new, empirically supported insights into the social significance of Roman games, and think about the ways that we can model factors like etiquette, emotion, and risk-taking, which we know from the historical record were strategic elements crucial to ancient social interaction.

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## 110. Rolling the Roman Dice: Experiencing Ancient Chance with AI

*Summer Courts (University of Reading)*

*James Goodman (Queen Mary University of London)*

*Timothy Penn (University of Reading)*

The study of historical board games offers crucial insights into past social structures, cultural interactions, and cognitive processes, yet foundational questions about how these games were played often remain unanswered. Conventional scholarship struggles to test hypotheses on a large scale due to the infeasibility of mass human playouts. Our research addresses this gap by applying Artificial Intelligence (AI)-driven simulation to explore the dynamics

of Roman board games, building on a very small sample of prior work in this area (as noted by Soemers et al. 2025).

In this paper, we provide some key insights into our groundbreaking work into two games played in the Roman period and widely attested on game-boards found at rural, urban and military sites across the Roman Empire: *pente grammai* and *ludus duodecim scriptorum*. We utilise the Tabletop Games (TAG) framework to test the impact of historical variables on several aspects of these games of chance, seeking to answer the key methodological question: How do computationally derived play metrics provide further insights into ancient players' experiences? This work positions itself as a proof-of-concept for the use of non-Large Language Model (LLM) AI to revolutionise understanding of ancient gameplay and its social implications.

The core method involves computational simulation using the Tabletop Games (TAG) framework, a specialist AI framework for generating measurable gameplay data (Goodman et al. 2024). TAG utilises AI methods based on Monte Carlo Tree Search (MCTS), which simulate human-level play by running thousands of game playthroughs and generating large-scale datasets impossible to achieve with human players alone. We ran two related sets of experiments were run:

- 1) First, comparing the impact of 'actual' (unfair) Roman dice from the archaeological record (Swift 2017) with idealised 'fair' dice when playing both *pente grammai* and *ludus duodecim scriptorum*. We wanted to test Swift's hypothesis that unfair dice, which favour 0s and 6s, would make for more exciting gameplay.
- 2) Second, testing the impact of *duodecim scripta*'s shift from two dice to three dice at some point after the 3rd century CE (Schädler 1999) on game dynamics. We sought to test the suggestion that the addition of a third die would make for a faster-paced, quicker game.

The simulation experiments generated a series of quantifiable metrics to measure the impact of changing play variables. The key results focused on metrics that assessed the effect of randomness on game outcomes, such as the average length of a game, first-player advantage, distribution of scores, and the frequency of lead changes (the 'drama' of the game). Specifically, the results quantified how unfair dice impacted gameplay, for example, by measuring whether they increased the number of lead changes compared to 'fair' dice. In experiment 1, we found that both rule variants for *ludus duodecim scripta*'s gameplay was largely unaffected by unfair dice, and only Kidd's version of *pente grammai* was impacted, resulting in much more quickly ended games, which were closer. This suggests that in most cases, 'unfair dice', which were probably shared by both players of a given game, might have made a game feel more exciting but did not ultimately change the outcome.

In experiment 2, we found that the addition of an extra die in *duodecim scripta* did not reduce the overall number of moves, though it probably reduced the number of turns, but this change in the rules resulted in a more complex game because players on average have more possible viable moves to choose between in each turn. Moreover, there was greater potential for reversals when playing with three dice rather than two and this 'drama' might have made the game more exciting to play.

This research provides a critical demonstration of the potential of AI-driven computational methods to address fundamental questions in cultural heritage. The findings contribute to the emerging field of historical games studies, establishing a proof-of-concept that will provide a jumping off point for further work in this space in future.

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## 114. Is Pente Grammai a playable game? Simulation as a third filter for rules reconstruction for historical games

James Goodman (Queen Mary University of London)

Summer Courts (University of Reading)

Timothy Penn (University of Reading)

Historical games rarely leave detailed rulebooks, and the reconstruction of plausible rule sets is based on relatively sparse clues. Classically two filters are applied; that the rules are compatible with the archaeological/iconographic evidence and with the literary evidence. Our research is on adding a third filter to these; that the game is playable. The methods extend previous work on Artificial Intelligence (AI)-driven simulation as a tool for historical game reconstruction (Browne 2023, Soemers et al. 2025; Crist et al. 2024) to a detailed case study of the ancient Greek game Pente Grammai ('Five Lines').

For Pente Grammai the archaeological evidence, such as the ubiquity of the inscribed five-line board in various settings, often etched into road surfaces or public spaces, indicates it was a common, quick game. Iconographic depictions, common on pots but also on a 3rd/2nd century BCE copper alloy mirror from Italy now in the British Museum (BM 1898,0716.4) also suggest that the game was widely played. Literary references also introduce the

importance of a 'move from the holy line' acting as an aphorism for a bold or risky move (Plato, *Laws*, V. 739-743; Plutarch, X.783b; Kidd 2017). There is also one pictorial representation of the game being played on a Greek vase. Based on these two established filters two distinct peer-reviewed rule sets have been reconstructed (Schädler 2009; Kidd 2017).

This paper utilises the Tabletop Games (TAG) framework (Gaina et al. 2020) to test the internal coherence and player experience of these dominant rule sets. We employed Monte Carlo Tree Search (MCTS) AI planning agents (Coulom 2006, Kocsis and Szepesvari 2006) to simulate thousands of games, enabling quantitative analysis impossible to achieve with human players alone. This simulation allowed us to examine core play metrics, including game length, the impact of randomness, and the level of skill required (Goodman et al. 2024a; Goodman et al. 2024b).

Our analysis reveals key structural issues with both current reconstructions. With either rule set, Pente Grammai is revealed to be a very low skill game and agents plateau in performance even faster than with Tic-Tac-Toe, which is comparably 2-4 times more 'difficult'. The game is also highly random, indicating that the outcome is frequently predetermined by the initial dice rolls, limiting player agency. Furthermore, while the Schädler rules are consistently very short, the Kidd rules technically allow games to continue ad infinitum. We also quantified the frequency of the 'move from the holy line' mentioned as a key feature in the literature. We find it is basically never observed in the optimal play of the Schädler rules but occurs occasionally in the Kidd rules.

These findings suggest that both current peer-reviewed rule sets may fail the third, crucial filter: playability. The outcomes, resulting in either trivial or endless gameplay with minimal skill demand, contradict elements of the archaeological and literary evidence - this raises questions about whether either monotony was an expected part of gameplay, or perhaps more likely, that we need to think again about the possible rules of Pente Grammai. We

conclude by suggesting that a third computational filter is essential to establish the validity of rulesets derived from the literary and archaeological evidence, which is often sparse and sometimes reflects abnormal play behaviours. We finish with an analysis of potential amendments to the Schädler/Kidd rules that, while remaining compatible with the first two filters, yield a more viable game experience.

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## 375. LUDITECH: Integrating Tactile Sensing and Computational Modelling in the Archaeology of Ancient Board Games

*Barbara Care (University of Fribourg)*

*Theodora (Dorina) Moullou (Hellenic Open University)*

The LUDITECH (LUDIc + TECHnology) project, recently funded by the Swiss National Science Foundation (SNSF) under the Spark scheme, introduces a new methodological framework within the emerging field of digital archaeo-ludology. The project aims to reconstruct the material and experiential dimensions of ancient board games by combining tactile sensing technology, computational modelling, and traditional archaeological analysis, Previous research has relied primarily on textual references, iconography, ethnographic analogy, or on computational simulations of rules. These approaches, while informative, offer limited insight into the physical traces of use preserved on the artefacts themselves. LUDITECH employs high-resolution tactile sensors capable of detecting sub-micron wear, scratches, and residues, thereby generating a new category of empirical data that documents the interaction between players and boards.



The study follows three interrelated research axes:

1. Validation of rule hypotheses by comparing simulated wear “heatmaps” with observed micro-traces;
2. Functional assessment, distinguishing objects used for play from those serving ritual or decorative purposes;
3. Manufacturing analysis, identifying tool marks and craftsmanship to infer production methods and skill levels.

Through the integration of tactile data and computational experimentation, the project reorients the study of ancient games from rule reconstruction toward questions of materiality, performance, and cultural context. Beyond ancient board games, the same methodology offers significant potential for investigating other categories of artefacts, such as inscribed or worn surfaces, and for developing interactive museum applications that connect the public with the sensory dimensions of the past.

## S33: Generative AI, Text Mining, and Semantic Modelling: Using Big Models for Big Problems, FAIRly!

*Alphaeus Lien-Talks, Historic Royal Palaces*

*Florian Thiery, Leibniz-Zentrum für Archäologie (LEIZA), Mainz, Germany & Research Squirrel Engineers Network, mail@fthiery.de*

**Location:** Hörsaal 02

**Session Format:** Standard (talks + closing discussion)

AI and ML are transforming archaeological research and heritage data work. This session highlights practical approaches for leveraging Generative AI, text mining [1], and semantic modelling/reasoning (e.g., CIDOC CRM/CRMarchaeo, RDF/LOD, SKOS thesauri, Wikidata) [2] to ensure that extraction, linking, validation, semantic reasoning, and reuse are schema-aware, explainable, and FAIR [3&4]. We want to highlight pipelines where knowledge graphs guide and constrain AI, and where semantic reasoning (rules, constraints, and logical inference) improves accuracy, transparency, and downstream interoperability [3,5].

This session aims for standard talks (research papers) and Lightning Talks (small on-going projects, scripts like little minions, etc.); please indicate what you want to present.

We particularly welcome papers from early researchers or from underrepresented communities.

### **Rationale and Scope**

AI and ML, especially Large Language Models and semantic reasoning, are rapidly reshaping archaeological research and heritage data work. Beyond the hype, we need evidence on when these systems help, when they harm, and how to make their outputs reusable and trustworthy. This session brings together:

- **Generative AI & Text Mining** (LLMs, IR, NER, OCR pipelines, prompt design, non-determinism), including graph-backed retrieval to ground prompts [1,6];
- **Semantic Modelling/Reasoning** (ontologies, knowledge graphs, entity linking, ontology alignment, SHACL validation) [2,3,5]; and
- **FAIR Using AI** (automated metadata extraction, FAIRification workflows, provenance, licensing, stewardship, reproducibility) [1,4].

Contributions should show how semantic models plug into AI methods end-to-end, e.g., graph-backed retrieval for prompts, ontology-aware IE, constraint-based post-processing, and inference over time/space, to deliver robust, reusable results [5&6].

#### Topics of Interest (include but are not limited to)

- GenAI for text generation, coding assistance, summarisation, translation, and data wrangling in archaeology.
- Information extraction from grey literature, reports, registers, and multimedia; OCR post-processing and layout-aware parsing.
- Semantic modelling & knowledge organisation: ontology design/extension (e.g., CIDOC CRM/CRMarchaeo), cross-walks, SKOS concept schemes and thesauri (e.g., AAT, FISH, PeriodO), knowledge graph construction; entity resolution across HERs, museums, archives, and research datasets; **semantic reasoning approaches and constraint validation** [2,3,5].
- Graph-augmented AI: SPARQL/graph retrieval (RAG) feeding LLM prompts; ontology-aware IE using preferred/altLabels and multilingual synonyms; mapping and reconciliation to CRM properties/classes; linking to Wikidata [6].
- Validation and reasoning in the loop: **SHACL/SHEx for constraint checking and repair; OWL reasoning for consistency and entailment; rule-based reasoning** (SWRL/SHACL-Rules/SHACL-SPARQL)

for temporal, spatial, and part-of relations; handling uncertainty and confidence propagation [5].

- FAIR with AI: automated metadata capture; FAIR assessments; PIDs; packaging and documentation; model cards and data cards for archaeological AI [1,4].

#### What We Ask from Contributors

- Transparent evaluation (report datasets, baselines, confidence/uncertainty, and error analysis):
  - IE/NER/classification: precision/recall/F1.
  - IR: top-k, nDCG.
  - Entity linking: accuracy/F1, ambiguity cases.
  - Ontology alignment: precision/recall/F1 on correspondences, mapping coverage, error types.
  - Reasoning/validation: consistency checks (pre/post), SHACL coverage (% shapes satisfied) and violation rates; competency questions via SPARQL (pass rate); entailment precision/recall on gold inference sets.
  - FAIR: metadata completeness, PID coverage, provenance depth, reproducibility score.
- Reproducibility: share code/models/data where possible. If restricted, provide synthetic examples or detailed protocols; include brief model/data cards and note energy/compute used.
- Pipeline clarity: include a diagram and artefacts (e.g., SHACL shapes, mapping tables, prompt templates, SPARQL queries, and reconciliation rules).

#### Intended Outcomes

- A shared view on when and how AI truly adds value in archaeology.
- Practical checklists for FAIR-by-design workflows (ingestion → triplification → IE/linking → KG-RAG → reasoning/validation → publication) [4-6].

- A starter kit: example **SHACL** shapes, CRM mapping stubs, KG-aware prompt templates, and SPARQL test suites (competency questions) [3,5&6].
- Connections across research, sector bodies, and data services to advance interoperable, ethical, and maintainable solutions.
- Ideas on how semantic reasoning creates new knowledge from unstructured and/or semantically modelled data.

### Accessibility & Ethics

We encourage accessible presentation materials, plain-language summaries, and disclosures on data sensitivity, cultural considerations, and potential harms. Work with restricted data should outline mitigation strategies (e.g., redaction, differential access). Please state open vs closed-world assumptions and how constraints affect the inclusion/exclusion of sensitive entities [4&5].

### Special Interest Group

This session is jointly organised by the CAA SIG on Artificial Intelligence and the SIG Data Dragon on Semantics and LO(U)D in Archaeology. The core aim of the SIGs is to utilise the SIG format to raise awareness of AI and Linked Open (Usable) Data in archaeology.

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|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>08:30 – 08:35</b> | Welcome and Introduction                                                                                                                                                                                                                                                                                                                         |
| <b>08:35 – 08:55</b> | 276. Extracting archaeological knowledge from legacy records: a human-in-the-loop approach using AI and NLP<br><i>Quirino Saraceni*</i> ; <i>Nevio Dubbini*</i> ; <i>Gabriele Gattiglia*</i> ; <i>Thomas Horrut (ENSEIRB-MATMECA – Bordeaux INP)</i> ; <i>Francesco D'Antoni (Sapienza University of Rome)</i><br><br><i>*University of Pisa</i> |
| <b>08:55 – 09:15</b> | 88. From Paper to FAIR: Orchestrating OCR, NER, and LLMs for Archaeological and Archival Data Accessibility<br><i>Alphaeus Lien-Talks (University of York, Historic England, Archaeology Data Service)</i>                                                                                                                                       |
| <b>09:15 – 09:35</b> | 129. AI in vocabulary-based subject metadata enrichment<br><i>Douglas Tudhope*</i> ; <i>Ceri Binding*</i>                                                                                                                                                                                                                                        |

*\*University of South Wales*

**09:35 – 09:55** 407. Text Mining archaeological reports for urban farming and fortifications: same approach, different results  
*Ronald Visser (Saxion University of Applied Sciences); Anja Fischer\*; Annika Blonk-van den Bercken (NMF Erfgoedadvies); Heleen van Londen\*; Arno Verhoeven\*; Morgan Schelvis\**

*\* Universiteit van Amsterdam*

**09:55 – 10:15** 404. Digging through archaeological data: Towards semantic search using neural retrieval models  
*Stelios Manousopoulos (ASCSA); James Herbst (ASCSA)*

**10:15 – 10:30** Discussion

**10:30 – 11:00** Coffee break

**11:00 – 11:20** 441. Talking Tablets: A Graph-Embedding Approach to Semantic Retrieval in Cuneiform Corpora  
*Daria Stefan (TU Wien); Florian Thiery (Leiza)*

**11:20 – 11:40** 217. Cuneiform Tablets and LLMs  
*Lee Drake (University of New Mexico)*

**11:40 – 12:00** 285. Automated Construction of a Geospatial Archaeological Knowledge Base for the Trans-Karakoram Region Using GraphRAG Agents  
*Tong Liu\*; Linru Xu\*; Jie He\**

*\*Harbin Institute of Technology, Shenzhen*

**12:00 – 12:20** 43. Can Generative AI Interpret Code Reliably? A Case Study in ChatGPT-Assisted Implementation of 3D Imaging Tools  
*Katrina Yezzi-Woodley\*; Samantha T. Porter\*; Jeff Calder\*; Pernu Menheer\*; Sofía Pacheco-Fores\*; Riley C. W. O'Neill\*; Peter J. Olver\**

*\* University of Minnesota*

**12:20 – 12:40** 221. How Sure Is a 60% Potter? Reasoning about Uncertainty in Archaeological Attribution using the Academic Meta Tool  
*Florian Thiery (LEIZA); Allard W. Mees (LEIZA)*

**12:40 – 13:00** 371. From Data to Insight: A Generative AI Workflow for Semantic Mapping and Trend Forecasting in Archaeological Literature  
*Edisa Lozić\*; Benjamin Štular\**

*\*Research Centre of the Slovenian Academy of Sciences and Arts*

**13:00 – 14:00** Lunch break

**14:00 – 14:20** 39. Multi-Model Deep Generative Restoration of Harappan Seals Using Advanced Architectures  
*Meriem Aoudia\*; Madeeha Balouch\*; Arwa Bayoumy\*; Imran Zuolkernan\**

*\*American University of Sharjah*

**14:20 – 14:40** 400. Seeing the Generated Past: How Editors and Readers Interpret AI-Created Archaeology Visuals  
*Aleksandra Cetwińska\**; Marcin Zarod (SWPS); Anna Gierojć (Independent); Adam Budziszewski\*; Konstanty Kowalewski\*; Julia Chyla\*

*\* Faculty of Archaeology, University of Warsaw*

**14:40 – 14:50** Discussion

## 39. Multi-Model Deep Generative Restoration of Harappan Seals Using Advanced Architectures

*Meriem Aoudia (American University of Sharjah)*

*Madeeha Balouch (American University of Sharjah)*

*Arwa Bayoumy (American University of Sharjah)*

*Imran Zuolkernan (American University of Sharjah)*

### 1. Introduction

Restoring ancient seals from the Harappan civilization (circa 2600-1900 BCE) is a profound challenge. The artifacts are not only fragile, but they also bear an undeciphered script, which makes any semantic or physical reconstruction highly problematic [1]. Physical conservation risks irreversible damage, and while digital inpainting is a non-invasive alternative, conventional methods often fail. They tend to produce blurry or structurally incoherent results, rendering them useless for the precise analysis archaeologists require.

Our work confronts this problem by systematically evaluating advanced deep generative models. We aim to answer two key questions: First, how well can modern architectures like GANs and Diffusion Models reconstruct missing

seal fragments, especially in preserving the fine-stroke integrity of the undeciphered script? Second, what evaluation protocols are needed to validate these computational restorations for actual archaeological use? Answering these questions allows us to establish a rigorous, reproducible framework for AI-assisted artifact restoration, bridging the gap between computational performance and archaeological needs.

### 2. Methods and Materials

Our research is built on a new, manually curated dataset of 1,058 Harappan seal images, sourced from key archival collections in Pakistan and India [2, 3]. We augmented this collection to 2,116 images to ensure robust model training, preparing separate grayscale and colorized versions to test performance across modalities.

The methodology involved a comparative evaluation of a full suite of inpainting architectures. After establishing a baseline with a pure convolutional U-Net, we implemented and trained three distinct GAN-based models (RFA-Net, Pix2Pix, DCGAN) and two Diffusion-based models (DDPM, Adversarial Diffusion). This multi-model approach allows for a robust comparison of generative paradigms. To evaluate them, we used a dual protocol: quantitative analysis with standard metrics (PSNR, SSIM, FID, LPIPS) for pixel and perceptual fidelity, and qualitative assessment against archaeological benchmarks to judge script continuity and textural realism.

### 3. Results

The quantitative results, summarized in Table 1, reveal clear architectural trade-offs. The GAN-based Pix2Pix model, for instance, excelled in pixel-level and structural fidelity (PSNR: 27.52, SSIM: 0.9150) on the grayscale dataset. RFA-Net, however, produced the strongest perceptual similarity (LPIPS: 0.0750), suggesting its outputs appear more natural. Diffusion models and the U-Net baseline provided stable benchmarks, with performance degrading consistently across all models when faced with the more complex colorized dataset.

Table 1: Key quantitative performance metrics on the grayscale dataset. (PSNR/SSIM higher is better; LPIPS lower is better).

| Model Architecture | PSNR (higher) | SSIM (higher) | LPIPS (lower) |
|--------------------|---------------|---------------|---------------|
| U-Net (Baseline)   | 23.46         | 0.8971        | 0.0812        |
| Pix2Pix (GAN)      | 27.52         | 0.9150        | 0.0562        |
| RFA-Net (GAN)      | 24.70         | 0.8850        | 0.0750        |
| DDPM (Diffusion)   | 23.20         | 0.8700        | 0.1265        |

Qualitative analysis reinforced these findings. Pix2Pix demonstrated the best script continuity, preserving the sharp strokes of the script. RFA-Net was superior at reproducing the subtle surface textures of the steatite. This highlights a key trade-off: some models excel at high-frequency detail (GANs), while others may be better suited for global coherence in heavily damaged areas.

4. Discussion

This work offers two primary contributions. For digital archaeology, it establishes a replicable, non-invasive workflow for virtually restoring fragile artifacts. By providing a benchmark dataset and a clear dual-evaluation protocol, we offer a foundational methodology that can be adapted for other classes of cultural heritage. This approach positions generative AI as a powerful conservation assistant, one that aids in visual restoration without making unsubstantiated claims about semantic decipherment.

For computer vision, the Harappan seals act as a unique and demanding benchmark for inpainting. The undeciphered script forces models to succeed based only on structural and stylistic patterns, with no semantic context to leverage. Our findings, therefore, illuminate how state-of-the-art architectures perform in this challenging, non-semantic, real-world domain.

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43. Can Generative AI Interpret Code Reliably? A Case Study in ChatGPT-Assisted Implementation of 3D Imaging Tools

*Katrina Yezzi-Woodley (University of Minnesota)*

*Samantha T. Porter (University of Minnesota)*

*Jeff Calder (University of Minnesota)*

*Pernu Menheer (University of Minnesota)*

*Sofía Pacheco-Fores (University of Minnesota)*

*Riley C. W. O'Neill (University of Minnesota)*

*Peter J. Olver (University of Minnesota)*

As generative AI becomes increasingly ubiquitous, it is reshaping how researchers mediate the use of code-driven tools. This raises the question of how best to leverage such approaches for understanding and modifying these tools. AMAAZE-labs is an interdisciplinary collaboration between archaeologists, computer scientists, and mathematicians. We recently released a Python-based semi-automated workflow for bulk scanning a wide range of objects and material types using micro-CT or medical-CT. The resulting TIFF stack or DICOM data are then surfaced to create research-quality 3D



models which require minimal human intervention (less than 10 minutes per scan) (O'Neill et al. 2024, Yezzi-Woodley et al. 2022). Following FAIR principles, these protocols have been made freely available on GitHub (<https://github.com/oneil571>) with sample data to allow users to try out the methods. However, many potential users who might be interested in applying it to their scanning needs, such as archaeologists, museum collection managers, and other researchers, might have limited knowledge of Python or 3D scanning and mesh processing. An increasingly common practice is to use generative AI such as ChatGPT to interpret and tweak protocols which calls to question the reliability of using AI-assisted code modifications.

Because LLMs are based on non-deterministic statistical models, output can vary in a way that undermines reproducibility and reduces reliability of research ready outputs. Choice of LLM (and version), the particulars of the prompt, and user-conditioned responses shaped by prior interaction history or stored preferences increase this variability, complicating efforts to attribute variation in outputs to the user or AI.

Here we present a discursive case study comparing the original mCT *En Masse* surfacing protocol (O'Neill et al. 2024) with versions implemented in several LLMs (e.g. ChatGPT, Gemini, and Replit) by an independent user---unaffiliated with the development of the original workflow---attempting to interpret and modify the code to run on a different operating system. In this case, the operator is a Senior Research Programmer with 20+ years of experience in general web/data scripting (Python, PHP, JS), with no prior experience in Micro-CT imaging, 3D scan data, biological anthropology, or archaeology. The goal is to use illustrative implementations to explore what “code interpretability” means in practice when generative AI is inserted into scientific workflows.

Though the mCT workflow used here can be applied to create 3D meshes of many types of objects, here we apply it to (1) a sample of teeth from an archaeological context and (2) synthetic data from primitives (e.g. cubes, spheres, tori) to increasingly irregular shapes. The archaeological sample consists of a collection of teeth from the San Martín Tilcajete archaeological sites in the Valley of Oaxaca, Mexico. The teeth were sampled with

permission of the Mexican Instituto Nacional de Antropología e Historia and in accordance with CARE principles.

We compare the code and mesh outputs from all workflows. The code is compared by assessing factors like code readability, runtime performance, and the degree to which code is altered, whether those changes are trivial syntactic differences, changes to the structure of the pipeline, or deep alterations to core algorithmic components. Mesh integrity is examined by aligning meshes and calculating basic distance measures to detect surface deviations. We examine whether any distortions or artifacts emerge during processing, and we examine how stability and reproducibility are affected by running multiple iterations on the same scan data.

We discuss the costs and benefits of using generative AI to navigate code learning in contexts where the outputs need to be research ready. We demonstrate why human interpretability and domain knowledge matter when AI is inserted into workflows. And, by interrogating the concept of “code interpretability” at multiple levels: syntactic (interpreting code form and structure), procedural (understanding the internal logic and framework underpinning the sequence of steps in the workflow), and semantic (the intended output as a representation of the real-world object) we demonstrate that interpretability does not reside solely in the LLM. We discuss the limitations of LLMs as tools for parsing, executing and adapting code as opposed to a stand-in for human understanding in a scientific workflow, arguing that if semantic preservation fails, then code interpretability has failed.

Preliminary results from LLM-mediated implementations of the workflow, in which both the original code and the accompanying publication were provided as input into ChatGPT-5.1, diverged from the original implementation. Resulting meshes exhibited inverted surface normals, mirrored geometry, and a failure to cross-reference the accompanying CSV file used to preserve specimen catalog numbers. Inverted normals are not concerning for invariant shape analysis, however, in instances where sign is relevant---such as biological forms where positive extrinsic curvatures correspond to cusps and negative extrinsic curvatures are associated with grooves---becomes

analytically consequential. Given sufficient expertise, inverted normals are trivial to diagnose and correct. Mirroring is a more serious concern because it flips the geometry across an axis and the object itself is no longer the same as the original. This transformation may not be easily detectable by the user. The original code is designed to handle mirrored scan data, however, this is a user-specified parameter which was missed in the LLM-generated implementation. Additionally, the failure to preserve specimen identifiers renders otherwise valid meshes epistemically incomplete by severing their connection to provenance and metadata. These breakdowns reflect alterations at the semantic, and even, the procedural level; workflow logic governing orientation, identity, and metadata was not faithfully preserved, despite being explicitly encoded in the original implementation. And, in all these cases, some level of human intervention was required to prevent or identify and correct errors that were not flagged by the LLM. Such breakdowns, without human intervention, bear semantic and epistemic consequences.

Research today is necessarily specialized. Anthropologists, imaging specialists, and software developers each hold domain expertise making outsourcing across domains both reasonable and inevitable and AI has become a tool for “translating” across domains. Yet, how to integrate

AI effectively remains poorly understood. This work is designed to encourage discussion on how AI-assisted workflows might be better structured and documented when utilizing workflows designed to produce research-ready outputs.

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## 88. From Paper to FAIR: Orchestrating OCR, NER, and LLMs for Archaeological and Archival Data Accessibility

*Alphaeus Lien-Talks (University of York, Historic England, Archaeology Data Service)*

Archaeological and heritage data trapped in inaccessible formats, whether digital grey literature or handwritten paper archives, remain largely invisible despite their irreplaceable value. This paper demonstrates how integrated artificial intelligence workflows combining Optical Character Recognition (OCR), Named Entity Recognition (NER), and Large Language Models (LLMs) can systematically address FAIR (Findable, Accessible, Interoperable, Reusable) data gaps while maintaining transparency, sustainability, and inclusivity. In particular, the workflows target accessibility through the creation of retrievable, structured outputs and metadata that support discovery and access (A1, A2), and interoperability by converting heterogeneous documents into formats that enable shared, machine-readable representation (I1).

Two complementary projects illustrate complete FAIRification pipelines. The Osteoarchaeological and Palaeopathological Entity Search (OPES) system applies rule-based NER with the MeSH ontology to bioarchaeological grey literature, achieving a F1-score of 0.889 (Precision 0.913 and Recall 0.868). The DigDoc excavation reports project processes handwritten and typed documentation through OCR and semantic structuring, reaching a Character Error Rate of 0.005.

Distinct workflows are tailored to material characteristics: OPES handles digital texts, while paper materials use OCR for capture, LLMs for correction, and automated metadata generation. An evaluation involving 83 participants, 26 experts, 42 students, and 15 public users yielded high accessibility ratings (mean > 6.0) and strong support from students, although experts emphasised the need for precision. Different pipeline stages benefit from different AI methods: LLMs for semantic enrichment, and rule-based NER for

transparent extraction. Lightweight approaches are sufficient for many tasks, while selective LLM use offers transformative potential without incurring unsustainable costs.

Overall, these projects demonstrate that comprehensive FAIRification of archaeological materials is achievable through strategic, interpretable AI workflows that connect technical innovation to sustainable heritage data stewardship. Given the centrality of AI components in these pipelines, the paper also considers the relevance of FAIR4ML as an emerging lens for responsible documentation and reuse of machine learning enabled workflows and outputs.

## 129. AI in vocabulary-based subject metadata enrichment

*Douglas Tudhope (University of South Wales)*

*Ceri Binding (University of South Wales)*

This presentation reports on a pilot investigation of the incorporation of AI (LLM) techniques in vocabulary-based subject metadata enrichment. The work takes place within the ATRIUM Project [1] as part of a task on text-based metadata enrichment where subject metadata is lacking and contributes to the project's FAIR semantic agenda.

An existing automatic, (URI) vocabulary-based, subject indexing recommendation (open source) system has been applied to the (Archaeology Data Service) OASIS archive of archaeological fieldwork events and associated grey literature [2], generating subject metadata recommendations, lists of span entities representing the annotated vocabulary concepts (with positions within input text). The pipeline is implemented using the spaCy library with a set of patterns expressed as Python modules and a series of specialised pipeline components. For the purposes of the ATRIUM demonstrator, the pipeline uses the FISH Archaeological Object Thesaurus and the FISH

Thesaurus of Monument Types (which will subsequently be mapped to the Getty Art and Architecture Thesaurus in the final demonstrator), together with specialised temporal and spatial elements. However, other vocabularies are also possible. In addition to numerical timespan expressions, archaeological named periods are taken from PeriodO. Currently the Historic England 'Archaeological and Cultural Periods' PeriodO authority is used but other PeriodO authorities are possible.

Good performance has been achieved with the pipeline when applied to the OASIS abstracts. Various specialised components apply pre-processing and token normalisation, NLP operations including Part Of Speech and lemmatisation, pairing of temporal and subject elements. The current focus is adapting the pipeline to operate on the Archaeology Data Service library of (historical) journal publications from a variety of publishers. Journal papers pose additional challenges in the variety of writing styles and a wider subject matter. The potential absence of Abstracts and also Conclusion sections in some publications (or minimal versions) requires the ability to process the full text of the article. On full text, the vocabulary-based subject metadata indexing pipeline will generate large numbers of annotations, matching the underlying subject vocabularies. While the full set of automatic metadata may be used to address use cases of highly specific search statements, a mechanism for ranking and prioritising some of the annotated vocabulary matches is the focus of current work. A variety of methods are being investigated, including concept frequency and position within the document structure.

One method under investigation is the application of AI (LLM) techniques to identify authorially important sections. This ongoing work makes use of structured prompts, full description of purpose, glossaries of contextual words and examples of input/output. The final output will form part of the pre-processing stages of the metadata enrichment platform, identifying relevant sections of the document, and feeding into the overall ranking/prioritisation algorithm applied to the vocabulary concepts identified by the

pipeline. Thus the final output remains the controlled vocabulary subject indexing metadata recommendations, provided via an open-source tool.

In our view, this approach is consistent with a responsible use of AI within archaeology. The AI component plugs into a broader pipeline that can provide an explainable rationale for the recommendations (with diagnostic data an option). It is being used in tandem with standard controlled vocabularies (SKOS thesauri) in the field. Thus AI is not being used to replicate what can already be well achieved by existing means but offers a contribution drawing on the contextual strengths of the underlying language model, rather than its wider general model. This has the potential to add a wider semantic field to the concept structure of the controlled vocabularies underpinning the metadata recommendations.

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## 217. Cuneiform Tablets and LLMs

*Lee Drake (University of New Mexico)*

Cuneiform records record numerous extinct languages—including Sumerian, Akkadian, Elamite, and Hittite—whose vast textual record far exceeds the capacity of the small number of trained specialists. Large Language Models (LLMs) offer a promising computational approach to assist in translation,

transliteration, and even the reconstruction of partially preserved texts affected by erosion or breakage.

This study outlines a multi-stage training framework designed to adapt modern LLMs for cuneiform analysis, consisting of:

1. Pretraining with span-corruption and autoregressive tasks to establish syntactic and morphological associations;
2. Supervised training for translation and transliteration;
3. Augmented training incorporating datasets with missing or damaged signs;
4. Corruption-aware fine-tuning to handle uncertainty and incomplete input; and
5. Language-specific specialization for individual languages.

Comparative results are presented across several architectures, including Meta's No Language Left Behind (NLLB), prompt-based UMT5 models, and character-level encoders such as ByT5. Performance varies by language, with Akkadian and Hittite achieving the highest accuracy and Sumerian posing persistent challenges. Larger models (>3 billion parameters) consistently outperform smaller ones, though translation quality remains highly sensitive to data normalization and task framing. These findings highlight that, in computer translation tasks, data curation is as critical as model scale in achieving meaningful linguistic reconstruction.

## 221. How Sure Is a 60% Potter? Reasoning about Uncertainty in Archaeological Attribution using the Academic Meta Tool

*Florian Thiery (LEIZA)*

*Allard W. Mees (LEIZA)*

Note: This is an abstract for a lightning talk, not for a full paper in this session

### Introduction

Archaeological attribution processes – such as assigning decorated Samian (terra sigillata) vessels to individual potters – are often based on probabilistic, stylistic, and geometric arguments. Yet, these steps – which are basically stages in a reasoning process resulting in a calculated conclusion – remain often implicit and challenging to reproduce. This lightning talk presents a semantic approach that formalises interpretative reasoning within CIDOC CRM and its extensions (CRMsci, CRMinf, AAAo). Using data from Samian Research and the ARS3D project, we explore how structured reasoning about uncertainty can be modelled and, in future, supported by generative AI systems.

### Material and Methods

The material used in an exemplary way is Roman decorated Samian. It was made in moulds and decorated by using figure type stamps. It was produced in different kilnsites and distributed throughout the Roman Empire. These decorated moulds have occasionally been signed by the potter who made them, but in many cases a signature is lacking, either caused by the incomplete preservation of the vessel or a signature has not been applied. Since many identical or very similar figure types occur with different potters, attributing a non-signed decoration to an individual potter is not trivial. To cope with this problem, there have been catalogues of figure types created

for some production centres. The existence of surmoulages of figure types makes it even more difficult to identify original and copied figure types. Hence, attributions of figure types or complete decorated vessels to potters remains a process comprising uncertainties. A formalisation of this process will help to make the attribution process more verifiable.

Building upon the Academic Meta Tool (AMT), we represent interpretative statements – observations, arguments, and attributions – as graph-based reasoning chains.

The Samian Attribution Ontology (SATO) extends the existing LADO ontology in order to describe multiple forms of evidence (geometric comparisons, quantitative analyses, stylistic judgements) and to quantify uncertainty.

The advantage of using AMT is that its reasoning can simulate cumulative uncertainties: For example: In an excavation context A, vessel 1 is attributed to potter X with 40 % confidence (dated 200–260 CE), vessel 2 to potter Y with 60 % confidence (dated 180–230 CE). An additional uncertainty may occur in a statement identifying a figure type after a geometric comparison, resulting in a 80% confidence that 2 figure types used by 2 different potters are identical. The reasoning engine calculates a combined date range for context A weighted by attribution confidence and may add a further weight to it based on the uncertainty within the figure type identification process.

This method allows the representation and propagation of uncertainty directly within the knowledge graph.

### Results

A prototype of the AMT reasoning module integrates the SATO model, enabling machine-interpretable representation of expert argumentation. It can aggregate evidence across multiple uncertain attributions, simulate confidence propagation, and visualise interpretative networks. The reasoning output – expressed in RDF – links quantitative and qualitative evidence, making interpretative logic transparent and reusable for further computational analysis. The verifiable reasoning process also results in a new approach related to the attribution of decorated Samian vessels to individual potters.

Adding a verifiable statement concerning the incertitude of any attribution is a far more realistic archaeological approach than the hitherto practised “finding the individual potter behind a decorated vessel”, often blurred by imprecise statements like “a decoration in the style / manner of potter Z”.

#### Discussion

Formalising interpretative reasoning bridges the gap between expert intuition and computational reproducibility. Integrating probabilistic reasoning within semantic frameworks opens the path toward AI-assisted interpretation and explainable attribution in archaeology. Future work will explore combining large language models for argument extraction with knowledge-graph reasoning for uncertainty management, providing a FAIR, transparent foundation for computational heritage interpretation.

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## 276. Extracting archaeological knowledge from legacy records: a human-in-the-loop approach using AI and NLP

*Quirino Saraceni (University of Pisa)*

*Nevio Dubbini (University of Pisa)*

*Gabriele Gattiglia (University of Pisa)*

*Thomas Horrut (ENSEIRB-MATMECA – Bordeaux INP)*

*Francesco D'Antoni (Sapienza University of Rome)*

#### INTRODUCTION

The archaeological record has been extensively documented since the late 19th century, producing an immense corpus of reports, notebooks, correspondence and administrative forms. However, most of this documentation, i.e. the so-called legacy data, remains locked in analogue formats or in digital but unstructured “grey literature”, using file formats from which data cannot be easily extracted (e.g. pdf, jpg). The lack of structured, machine-readable data significantly limits the reuse, interoperability, and accessibility of archaeological knowledge. Manual digitisation and information extraction from these sources are time-consuming and expensive, requiring expert interpretation and domain-specific knowledge, and are often impossible to carry out.

In recent years, Artificial Intelligence (AI) and Natural Language Processing (NLP) have shown great promise in automating parts of these processes, particularly through Optical Character Recognition (OCR), Named Entity Recognition (NER), and, lastly, transformer-based Large Language Models (LLMs). Yet, the heterogeneous nature of archaeological documentation, ranging from digital-born reports to typewritten or handwritten excavation notes, poses substantial challenges for automated systems. This work addresses the problem of extracting structured archaeological information from legacy documents by developing and evaluating an information extraction workflow that combines AI-based tools with expert-driven validation.



The study focuses on defining a robust methodology for automatically identifying and structuring key entities from unstructured texts, while ensuring data reliability through a human-in-the-loop validation process. The work draws upon the MAGOH database (Managing Archaeological data for a sustainable Governance of the Heritage) as a test environment, encompassing over 10000 excavation records from the provinces of Pisa, Florence, Prato, Pistoia, and Lucca, Italy (Anichini et al. 2023).

## MATERIALS AND METHODS

The workflow integrates several components: document digitisation via OCR, information extraction and summarisation using NLP and LLMs, and human-in-the-loop validation.

### 1. Data source and preprocessing

The dataset consists of approximately 10000 excavation records from MAGOH, including digital-born and scanned PDF documents. Preprocessing steps convert these into machine-readable text using OCR methods, including classical machine learning (Tesseract) and vision LLM (Google Gemma). Preprocessing also includes noise reduction, de-skewing, and removal of irrelevant sections.

### 2. Language model fine-tuning and entity extraction

Rather than fine-tuning a pre-trained model, which is computationally intensive, the system employed an open-source GPT architecture as a zero-shot information extractor. Each document was first segmented and ranked using NLP techniques based on NER (Seow et al. 2025), such as keyword extraction, sentence embedding similarity, and relevance scoring. Only the most contextually relevant chunks were then submitted to the LLM model through structured prompts designed to identify key archaeological entities - i.e. site name, stratigraphic unit, material type, chronological attribution, and geographic reference - exploiting the capabilities of the DSPy (Khatab et al. 2024; 2022) library, which replaces manual prompts with trainable, self-improving and reusable components.

### 3. Human-in-the-loop validation

Recognising the semantic ambiguity and contextual variability of archaeological texts, the workflow integrates a human-in-the-loop validation stage. For each extracted piece of information, the system highlights the exact text lines in the original document from which the data were derived, enabling operators to visually inspect and verify the extraction context at any time. Each output is also accompanied by a confidence score, allowing low-confidence results to be automatically flagged for expert review. Human operators can thus focus their attention on uncertain or ambiguous cases, ensuring that the validated information is both accurate and traceable.

### 4. Evaluation

Model performance was evaluated against manually annotated test sets. Quantitative metrics assessed accuracy in entity recognition and summarisation, while qualitative feedback from archaeologists evaluated interpretability, usefulness, and trustworthiness of the system outputs. Time efficiency and error rates were also compared to manual data entry baselines.

## RESULTS

The initial results demonstrate the potential of hybrid AI-human workflows to accelerate the structuring of archaeological legacy data. vLLm OCR and preprocessing achieved conversion accuracy >95% for typewritten and image documents. The fine-tuned LLM achieved an F1-score of approximately 0.82 in entity recognition tasks. The human-in-the-loop process proved critical for improving reliability. Experts were able to correct errors rapidly using an intuitive interface, reducing validation time by nearly 90% compared to traditional manual data entry. Furthermore, iterative feedback loops significantly improved model performance over time, particularly in the recognition of rare or context-dependent terminology (e.g., the identification of the excavation site in the documents exceeded 70% accuracy).

## DISCUSSION

This study contributes to ongoing efforts to bridge AI methodologies and archaeological data management by demonstrating a scalable, domain-adaptable workflow for extracting structured knowledge from legacy texts. It highlights the advantages of combining machine efficiency with expert oversight, addressing one of the key challenges in digital archaeology: balancing automation with interpretative quality.

The results underscore several broader implications for archaeological data management and digital scholarship. The transformation of legacy documentation into machine-readable and interoperable formats enhances the Findability, Accessibility, Interoperability, and Reusability of archaeological information, fully aligning with the FAIR data framework and the European vision for digital cultural heritage. Methodologically, the use of LLMs for archaeological information extraction demonstrates how general-purpose AI systems can be effectively adapted to domain-specific languages when guided by curated data selection and expert validation. At the same time, the workflow offers a sustainable and scalable path for large-scale digitisation, by reducing manual labour and leveraging open-source models, with a modular architecture that can be readily extended to other cultural heritage datasets such as museum catalogues or archival inventories.

Beyond technical innovation, the integration of AI into archaeological interpretation raises critical epistemological questions concerning accountability and reproducibility. The human-in-the-loop design developed here provides a practical solution, maintaining interpretive oversight while harnessing the efficiency of automation.

Nonetheless, challenges remain: handwritten scans continue to hinder OCR accuracy, while the semantic ambiguity of archaeological descriptions complicates entity disambiguation. Moreover, the variability of legacy data formats requires adaptable extraction strategies and continuous refinement of relevance models. Despite these limitations, the study demonstrates that AI-assisted information extraction can substantially accelerate the structuring of archaeological records while preserving the scholarly rigour and contextual depth essential to archaeological research.

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## 285. Automated Construction of a Geospatial Archaeological Knowledge Base for the Trans-Karakoram Region Using GraphRAG Agents

*Tong Liu (Harbin Institute of Technology, Shenzhen)*

*Linru Xu (Harbin Institute of Technology, Shenzhen)*

*Jie He (Harbin Institute of Technology, Shenzhen)*

The Karakoram Range, as a natural barrier along the ancient Silk Road from Xinjiang to South Asia, forms a high-altitude corridor that serves as a key locus for regional trade, cultural exchange, and religious diffusion. Centuries of cross-cultural interaction have accumulated numerous archaeological sites across the Trans-Karakoram region. However, the region's extreme terrain and climate severely constrain the breadth and systematization of archaeological surveys. Since the 19th century, when the British Indian government

conducted scientific mapping of the region, numerous explorers, surveyors, and archaeologists have documented site information through travelogues, maps, colonial archives, and excavation reports. The construction of the Karakoram Highway in the 20th century further facilitated cross-national collaborative archaeology (Dani 1983), leading to a dramatic increase in archaeological materials. However, these texts are highly fragmented, with significant differences in source, language, style, and production context, resulting in contradictions and overlaps in site names, location descriptions, event details, and chronological assessments. The lack of a systematic mechanism for aligning and resolving conflicts across materials—especially in contexts involving cross-lingual and cross-temporal datasets—remains a core bottleneck in regional heritage research, a challenge that traditional manual approaches and conventional NLP methods struggle to address.

In the age of digitization and big data, texts remain the most direct and information-dense archaeological materials. Unlike the "discovery" of sites through satellite imagery, texts provide essential archaeological evidence, such as names, dates, functions, event contexts, and interregional relationships, especially when sites are buried, destroyed, or when ground-based evidence is difficult to obtain (Cooper and Green 2016). With the rapid development of computational archaeology methods and large language models, archaeologists can now process vast amounts of textual data, enabling automated knowledge extraction and analysis. This has opened new opportunities to overcome the limitations of traditional archaeological methods. However, the heterogeneity of textual materials and the challenges of cross-disciplinary knowledge integration remain, particularly as generative AI lacks domain-specific constraints and is prone to hallucination or reasoning errors. Retrieval-augmented generation (RAG) improves model control over the domain, while GraphRAG, based on graph structures, further enhances cross-source alignment, relationship reasoning, and community detection, providing structured support for complex archaeological knowledge reconstruction. Therefore, this study proposes an AI framework based on GraphRAG, focusing on resolving the cross-material knowledge alignment issue, and

aims to automate the extraction and reconstruction of site information from archaeological materials across the Trans-Karakoram region.

This study, with GraphRAG at its core, couples knowledge ontologies, toponym encoding, and graph-based reasoning to create an integrated workflow for text-based knowledge extraction and geographic entity reconstruction. Taking the Hunza, Gilgit, Ghilas, and Swat regions as case studies, the following steps were undertaken: (1) the construction of a database composed of travelogues, survey archives, and archaeological reports, along with the creation of historical and modern toponymic mapping tables and databases to reduce toponymic variance and cross-linguistic discrepancies; (2) the development of a knowledge ontology model based on site-specific textual features, incorporating spatial orientations, site types, preservation features, related figures, and chronological relationships into a unified semantic framework; (3) the creation of an "OCR—Document Segmentation—Knowledge Graph Construction—Community Detection—Vectorization—Graph-based Reasoning" AI pipeline for automated identification of conflicts across materials, facilitating entity alignment and relationship validation; (4) integration of a toponym database and geographic encoding to generate an enriched spatial database for archaeological sites; and (5) evaluation of model performance through semantic extraction precision, toponym matching rate, and knowledge alignment consistency metrics. Ultimately, this study establishes a computable and scalable geographic archaeological knowledge framework for the Trans-Karakoram region, enabling the automated extraction and alignment of multi-source heterogeneous materials and providing new evidence for identifying the spatial distribution of sites and cross-regional interactions in the high-altitude corridor.

Historically, incomplete and discontinuous datasets have limited archaeologists' ability to study ancient landscapes. The text-based knowledge construction approach proposed in this study, based on GraphRAG, overcomes the limitations of traditional manual methods in terms of efficiency and consistency, allowing for the automated integration and computational

reasoning of historical texts, colonial archives, and archaeological records. In the broader context of Silk Road archaeology and transnational heritage research, particularly in light of UNESCO's recent push for "transnational heritage nominations" and "comprehensive recognition of the Silk Road corridors" (Williams 2016), the methodology presented in this study provides a foundational automation toolchain for heritage identification and cultural landscape interpretation in frontier regions. Additionally, it has the potential for migration and reuse in regions with similar historical contexts and textual structures, such as South Asia and Central Asia.

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## 371. From Data to Insight: A Generative AI Workflow for Semantic Mapping and Trend Forecasting in Archaeological Literature

*Edisa Lozić (Research Centre of the Slovenian Academy of Sciences and Arts)*

*Benjamin Štular (Research Centre of the Slovenian Academy of Sciences and Arts)*

The paper will demonstrate the use of generative artificial intelligence (GenAI) for semantic data mapping, coding assistance, summarization, and information extraction from literature. The case study is a bibliometric analysis of the 2,500 most cited archaeological publications, aiming to identify past trends and model near-future trends in archaeology.

**Materials and methods.** The data was sourced from app.Dimensions.ai, a service that uses black-boxed AI methods for data compilation. Nomic Atlas was then used for semantic mapping of the data, a method based on LLM-powered embeddings. Next, code generated by generative AI was used to create a machine learning (ML) workflow to calculate the attention index. This index was used to extract past trends and model near-future trends in archaeology. **Results.** One of the most important results in semantic data map hosted by Nomic Atlas titled "Archaeological research dataset." (1) The semantic map represents 10 knowledge domains in archaeology, further subdivided into 98 knowledge subdomains. The map is free to explore and can be used for bibliometric studies, teaching archaeology, planning personal or institutional research agendas, and more. The attention index, calculated for each of the 2,500 publications for each year since publication, enabled us to explore and precisely map past trends in archaeology. In addition, future trends have been modeled for each of the 98 knowledge subdomains. All tools and all data not protected by original copyright will be made freely available.

**Discussion:** why it matters? Immediate results offer insight into trends in archaeological science. However, for this presentation and this audience, secondary insights into workflows are more important. Specifically, this

workflow can be applied to any text-rich tabular, for example documentation from an archaeological excavation. In our presentation, we will focus on demonstrating the workflow and will not avoid discussing the shortcomings and even mistakes caused by AI tools, nor will we ignore what is now very easy to accomplish, even if it still impresses observers.

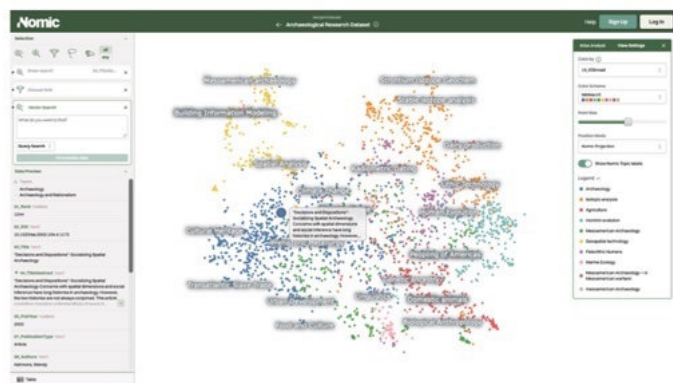


Figure 1. Semantic mapping of knowledge domains in Nomic's Atlas (1).

Funding: This research was part of the ARTEMIS project that has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement n° 101188009, and the Slovenian Research and Innovation Agency (ARIS) grant number P6-0064.

(1) <https://atlas.nomic.ai/data/benjaminstular/archaeological-research-dataset/map>

## 400. Seeing the Generated Past: How Editors and Readers Interpret AI-Created Archaeology Visuals

*Aleksandra Cetwińska (Faculty of Archaeology, University of Warsaw)*

*Marcin Zarod (SWPS)*

*Anna Gierojć (Independent)*

*Adam Budziszewski (Faculty of Archaeology, University of Warsaw)*

*Konstanty Kowalewski (Faculty of Archaeology, University of Warsaw)*

*Julia Chyla (Faculty of Archaeology, University of Warsaw)*

Generative AI (GenAI) images are increasingly used to illustrate archaeology online. They promise speed and reach, yet risk anachronism, stereotype reinforcement, and “automated pareidolia” in a discipline that already reconstructs past worlds from fragile and fragmentary evidence. Despite active ethical debate, there is limited empirical evidence on (i) how content creators actually deploy GenAI visuals of the past and (ii) how online recipients interpret them in terms of engagement, recognizability, and credibility. This paper reports a mixed-methods study of the reception of AI-generated visuals of the past, based on the unique practice of the Polish popular-science blog Archeowieści, aimed to identify where intent–interpretation gaps arise and how to mitigate them through clearer role labelling and content policy. Archeowieści, a portal run by researchers, PhD candidates, and students, affiliated with a Polish university research unit, promotes archaeology, scientific discoveries, and archaeological heritage. Over the past three years, it has published nearly 300 original popular-science articles, and for the last two years, it has used generative AI tools (e.g., Midjourney) to create some of the covers accompanying their publication.

This „long-term” practice, carried out by a group of science communicators embedded in the academic environment and dedicated to sharing specialized knowledge with the public, made it possible to approach the issue of the reception of AI-generated visuals of the past from three complementary

perspectives based in Participatory Action Research (PAR) methodology: i) content analysis, summarizing the portal's actual visualization practices in producing main covers for archaeological themed posts on blog; ii) in-depth editorial interviews (IDI methodology), which revealed the motivations, attitudes toward science communication, and rationales behind the use of AI tools; and iii) an online survey (n = 689) including an opt-out experimental block, which demonstrated how the practice of employing generative AI visualizations of the past is perceived by the recipients.

In this paper we thus provide an evidence-based account of how GenAI visuals are actually employed in practice, highlighting where they help (timeliness, reach) and where they may harm (false authenticity, role confusion). Rather than ban or celebrate GenAI, the findings support two practical measures: (1) explicit role labels in captions ("editorial illustration," "artist's impression," "scientific reconstruction") and (2) brief contextual notes on what is known vs. imaginative fill-in. These interventions reduce misinterpretation without depressing engagement.

While our study centres on empirical evaluation of GenAI in communication (not model building), it contributes to session's goal of trustworthy, reusable practice by specifying clear editorial policies and label designs that can be embedded in FAIR-minded workflows. We will release the survey instrument, codebook, and debrief template to support reuse and cross-site replication.

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#### 404. Digging through archaeological data: Towards semantic search using neural retrieval models

*Stelios Manousopoulos (ASCSA); James Herbst (ASCSA)*

##### Introduction

Archaeological research increasingly depends on the ability to retrieve and interpret information from large corpora of unstructured textual data, including excavation notebooks, field reports, catalogued artifacts and scholarly publications. While formalising and standardising data through controlled vocabularies and conceptual models remain central to information organisation, the need for free-form descriptive text persists. Such text captures contextual detail that structured metadata alone cannot convey, yet its enrichment with controlled terminology requires extensive manual labour and expert oversight. Given the volume and heterogeneity of legacy data accumulated over more than a century of fieldwork, comprehensive manual enrichment in practice remains unattainable. The urgency of this challenge is growing: advances in optical character recognition (OCR) are unlocking vast new corpora of digitised archival materials.

Traditional information retrieval (IR) in archaeology remains largely lexical, relying on keyword matching that struggles to capture the conceptual variation and contextual nuance of local and specialist terminology. These include



fuzziness, where the same term may denote different concepts (e.g., context as a stratigraphic unit or a findspot); synonymy, where different terms are used for closely related entities (e.g., skyphos and kotyle for comparable vessel types); and implicit semantic hierarchies, where broader categories are described through more specific descriptive or typological labels (e.g., drinking vessel classified as kylix, cup, or kantharos). A query like “prehistoric drinking vessels” may be expected to match material recorded under more specific terminology, including Late Helladic kylikes or cups dated to the early 12th century BCE. Similarly, a search for “medieval child burials” would be expected to surface passages referring to infant or subadult interments within Byzantine or Frankish contexts. In keyword-based retrieval systems, relevant material is difficult to locate for archaeologists seeking parallels, as well as for students and non-specialists without prior knowledge of specialist terminology.

Recent work applying transformer-based natural language processing to archaeological corpora

(Brandsen et al. 2022) demonstrates that domain adaptation of language models can enhance

discovery and extraction tasks. Motivated by these developments, our research explores how neural retrieval models can support semantic search over English-language archaeological documentation by representing documents and queries in a shared semantic vector space that captures expert vocabulary, synonymy, and conceptual relationships.

### Approach

We investigate a flexible, multi-stage neural retrieval pipeline inspired by advances in semantic IR. The architecture considers (1) dense vector representations (Karpukhin et al. 2020), (2) late-interaction retrieval (Khattab and Zaharia 2020), and (3) cross-encoder reranking (MacAvaney et al. 2019), allowing experimentation with different retrieval depths and model configurations. Dense vector embeddings represent each document as a single vector capturing overall semantic content, and similarity is computed using cosine

distance. Late-interaction models retain token-level embeddings for more granular matching between query and document terms, typically aggregating token similarities via a maximum or sum operation. Cross-encoders jointly encode query–document pairs and compute similarity through direct attention-based interaction over the combined sequence, yielding the most context-sensitive relevance estimates.

At its core, the system uses transformer embeddings adapted to archaeological language through self-supervised contrastive training on English-language texts from the ASCSA Corinth Excavations archive, where contrastive signals arise implicitly from the structure and distribution of in-domain text rather than from explicit relevance annotations. Depending on configuration, these vectors can serve directly for approximate nearest-neighbour search or form the basis of a late-interaction index that preserves token-level context, as in the ColBERT family of models (Khattab and Zaharia 2020). A cross-encoder can then be applied as an optional reranking stage for fine-grained contextual relevance scoring.

This retrieval pipeline is being developed as part of a broader archaeological data platform under the governance of the American School of Classical Studies at Athens (ASCSA). The platform augments established browsing and filtering workflows with semantic search and is intended to be made publicly accessible over published excavation data.

### Evaluation

This retrieval pipeline is being developed as part of a broader archaeological data platform under the governance of the American School of Classical Studies at Athens (ASCSA). The platform augments established browsing and filtering workflows with semantic search and is intended to be made publicly accessible over published excavation data.

Retrieval effectiveness is measured using recall@50, precision@50, F1, and nDCG@10. Recall captures coverage, precision captures usefulness, and F1

summarises the balance between the two in exploratory search; for these metrics, documents graded as 1 or 2 are treated as relevant. nDCG@10 evaluates ranking quality by rewarding the placement of highly relevant documents near the top of the result list.

## Results and Discussion

Preliminary experiments demonstrate substantial gains over baseline keyword retrieval and reveal the potential for richer, concept-based search. Across all retrieval architectures, domain-adaptive fine-tuning on archaeological text consistently improves performance compared to non-domain-tuned models, most notably through higher recall@50, indicating improved coverage of relevant catalogue entries and report passages during exploratory search. When comparing retrieval architectures under domain-tuned conditions, late-interaction-first models offer the best balance between effectiveness and efficiency. They deliver substantial gains in both recall@50 and nDCG@10 relative to dense-only configurations while remaining practical for large-scale retrieval. Dense retrieval remains the most computationally efficient and scalable option, whereas cross-encoder reranking achieves the highest ranking accuracy, particularly in terms of nDCG@10, at substantially higher computational cost.

More broadly, these findings suggest that multi-stage neural retrieval architectures can improve access to archaeological knowledge across heterogeneous corpora without replacing existing documentation practices. By supporting semantic discovery over published excavation data and integrating with established research platforms, such approaches offer a scalable means of improving the discoverability, interoperability, and reuse of archaeological information.

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## 407. Text Mining archaeological reports for urban farming and fortifications: same approach, different results

*Ronald Visser (Saxion University of Applied Sciences)*

*Anja Fischer (Universiteit van Amsterdam)*

*Annika Blonk-van den Bercken (NMF Erfgoedadvies)*

*Heleen van Londen (Universiteit van Amsterdam)*

*Arno Verhoeven (Universiteit van Amsterdam)*

*Morgan Schelvis (Universiteit van Amsterdam)*

Text mining was applied in two different projects using similar approaches with varying results. In both cases no AI was used, because this was not needed. Both projects were aimed at synthesising archaeological reports and grey literature. The first project was on urban farming, the second on walls and other fortifications in towns/cities. In the project on urban farming the research was aimed at finding patterns and the extent of food production in towns, focussing on husbandry, fish farming horticulture and arable farming. The project on fortifications was aimed at synthesising where and how towns were fortified, mostly before the advent of gun powder. Both projects tried to ascertain historical developments.

Urban farming is about food production for and by town dwellers and is partly known from documentary evidence. While research on urban farming in the Netherlands exists, the topic has nevertheless remained relatively underexposed in terms of historical, archaeological and archaeobotanical research. In a recently published volume, evidence for urban farming in Dutch towns between 1250 up to 1850 has been presented (Fischer et al. 2021). In this synthesizing research we applied an innovative method that combines text mining with conventional reading and analysing (grey) literature from commercially funded urban excavations in the Netherlands carried out between 1997 and 2017. A list of relevant (archaeobotanical) keywords was

used to mine the text of 1380 published reports. Each report was firstly converted to text, and if needed Optical Character Recognition (OCR) was applied to the PDF. A Term Document Matrix (TDM) was created for each document with the frequency of each word in the document. These words were matched with the keywords in a database. Based on the frequency of the keywords all reports were scored and the highest scoring reports were also found to be the most relevant for our research. This method was used to filter relevant reports for further in-depth analyses, generating diachronic data on historic farming in 84 towns. The method that we applied is innovative, transparent and open. We have made all code of the analyses available (Visser 2022), because we value Open Science and reproducibility. In the research quantitative and qualitative approaches were combined to understand the nature of urban farming in the Netherlands, resulting in the discovery of small details and large patterns during this long and dynamic time period. In this interdisciplinary paper we will explore three main themes: methodology, results and future applications for and beyond archaeobotany.

Due to the successful approach on urban farming, we applied the same methodology on a project in relation to fortifications in cities and towns. While we developed the method in the first project in 2019-2020, before Large Language Models became popular, the simplicity and reproducibility of the approach made it a logical choice to continue with this approach with a different subject. In this case it made more sense not to use AI, rather than to use AI. In this project we used a larger dataset of archaeological reports from 123 cities and towns, in total 7155 PDF-files. Based on the text mining using keywords various patterns could be discerned. Various quantitative and spatial patterns were observed, leading to various insights. However, the reports contained much more fragmented information, leading to less detailed results than with urban farming.

These different results show the advantages and shortcomings of the approach and in this presentation we will compare these two projects and discuss the lessons learned. We will start with a short overview of the results of both projects and then present a discussion of the evaluation, including the limitations of both the datasets and the results.

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## 441. Talking Tablets: A Graph-Embedding Approach to Semantic Retrieval in Cuneiform Corpora

*Daria Stefan (TU Wien)*

*Florian Thiery (Leiza)*

### Introduction

Recent research in the digital study of cuneiform highlights a persistent tension between symbolic methods, which ensure interpretability and scholarly control, and data-driven approaches, which enable semantic generalization but lack transparency. This challenge is particularly pronounced for ancient texts, where meanings are sparse, polysemous, and historically situated. Building on this perspective, the present work adopts a hybrid framework that combines a curated knowledge graph with sense-level embeddings to support semantically informed and explainable retrieval of cuneiform tablets.

### Methodology

This work proposes an initial end-to-end methodology for building a semantic knowledge and retrieval system for cuneiform tablets, integrating

symbolic knowledge representation with subsymbolic embedding-based retrieval. The approach is grounded in the MaiCuBeDa and MaiCuBeDaHT databases, which provide richly annotated 3D scans of tablets, inscriptions, annotations and metadata in form of a knowledge graph.

### Data Acquisition and Symbolic Knowledge

The symbolic layer is constructed from MaiCuBeDa and MaiCuBeDaHT data, which include tablets, inscriptions, glyphs (graphic symbols), and characters (semantic units). These entities are organized in a knowledge graph that connects tablets to glyph occurrences, glyphs to characters, and characters to their Unicode representations. Canonical lexemes with L-codes, Senses with Q-codes, languages (Sumerian and Akkadian), and historical periods are extracted from Wikidata and aligned with the graph via shared Unicode signs. While the original knowledge graph is CIDOC CRM compliant, senses are represented using specialized lightweight ontologies such as SKOS or FOAF, to ensure sufficient expressivity while reducing the number of links needed to express standard relationships. This provides explicit provenance, semantic precision, and stable identifiers, forming the authoritative foundation for subsequent subsymbolic processing.

### Subsymbolic Knowledge Representation

On top of the symbolic graph, subsymbolic representations are introduced in the form of embeddings generated at the Sense level. These embeddings encode semantic relations between meanings, enabling the system to identify conceptual proximity across different lexemes and languages. By anchoring embeddings to explicitly defined Sense entities, the approach preserves a clear correspondence between vector representations and symbolic referents. Distributional uncertainty inherent in embeddings is acknowledged, reported and constrained: similarity scores are used only transiently for query expansion and ranking, never asserted as new facts or persisted in the knowledge base.

### Embedding Models and Evaluation

This paper focuses on evaluating four retrieval strategies:

The first approach embeds Sense texts using pretrained sentence-transformer models (e.g. all-mpnet-base-v2, paraphrase-multilingual-mpnet-base-v2, LaBSE) and optionally refined through lightweight contrastive fine-tuning.

The second approach applies knowledge-graph embedding models (e.g. TransE, RotatE). Input consists of triples encoding relations between Lexemes, Senses, and higher-level semantic categories (e.g. *Lexeme—hasSense—Sense*, *Sense—isA—KinshipTerm*). The resulting vectors encode structural regularities, preserving relational constraints in the embedding space. Output vectors capture logical and ontological proximity rather than textual similarity, supporting polysemy modeling and relation-based inference, but offering limited support for free-text or abstract user queries.

The third approach combines both representations by generating both a text-based embedding and a graph-based embedding for each Sense entity and fusing them into a composite representation. This strategy aims to improve disambiguation accuracy and robustness in sparse data settings, at the cost of increased engineering complexity and tuning effort.

The fourth approach serves as a purely symbolic baseline, relying exclusively on explicit FactGrid relations without vector similarity

Evaluation is conducted through a controlled retrieval experiment over a fixed, semantically annotated corpus of tablets and a set of test queries, associated with a curated ground-truth set of Senses. Performance is measured using precision@k, recall@k, and mean reciprocal rank, with additional analyses of sense-level disambiguation accuracy for polysemous lexemes, explainability cost as given by the number of symbolic links required to justify a retrieved result, coverage, and robustness to query variation.

#### FAIR Data and Metadata Management

Reproducibility and transparency are ensured through stable identifiers for all symbolic entities, versioned embedding models, documented training or fine-tuning procedures using FAIR4ML, and model cards. Semantic retrieval remains explainable by re-grounding all results in explicit graph paths linking

tablets to inscriptions, signs, lexemes, and senses, together with their source metadata. Because embeddings operate at the Sense level and are applied only at query time, updates to models or parameters affect ranking behavior without altering curated knowledge.

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## S34: Modelling Seafaring: Methodological Retrospective and Future Roadmap

*David Gal, University of Haifa*

*Karl Smith, University of Oxford*

**Location:** Hörsaal BIG

**Session Format:** Standard

This session aims to focus on the methodological realm of modelling seafaring. It solicits the showcasing of modelling experiences, including choice considerations, modifications to existing models, tests conducted, and ideas for the future. The session aims to help identify and prioritise the elements of seafaring modelling and its application, contributing towards the goal of an emerging formalisation of such modelling in future research.

Modelling of historic seafaring is not a new undertaking, and it has become increasingly prevalent in the last decade, supporting maritime connectivity studies. The introduction of methods to model seafaring has primarily been an unorchestrated effort of individual researchers or laboratories. (Perttola & Slayton, 2024, p. 2). Two separate paradigms have emerged in recent years. Most studies have employed GIS cost surface analysis, which is drawn from terrestrial movement modelling tools, with adaptations to maritime modelling. (Alberti, 2018; Leidwanger, 2013; McLean & Rubio-Campillo, 2022; Safadi & Sturt, 2019; Trapero Fernández & Aragón, 2022). Others have drawn methods from the nautical sphere, such as weather-routing software packages. (Gal et al., 2021; Warnking, 2016). The GIS cost surface analysis tools have been pushed to new limits, including batching sequential simulations, to overcome the limitation of static averaged wind data. (Perttola, 2021; Perttola & Slayton, 2024). However, they are not without significant drawbacks, such as the inability to incorporate waves, sea currents, and the human factor in modelling.

The validity of using averaged wind data has been questioned; yet many recent studies remain reluctant to abandon this paradigm. The leading presumption for the use of averaged environment is that it reflects the average of all sailings. (Scheidel et al., 2012), while the presumption of the input of a large sample of wind at high temporal resolutions is that it maintains knowledge of the variability of the winds, and that these constitute the windows of favourable winds, which are key for Mediterranean sailing mobility. Multiple simulation runs on a large sample of non-averaged environmental data facilitate a statistical spread of output measures.

Mariners would pick and choose when conditions suited departure on a sailing passage with favourable winds, and they would be prudent in avoiding severe weather conditions. Such reasoning needs to be implemented in seafaring modelling. The human factor may be introduced to the simulation process through agent-based modelling (Davies & Bickler, 2013; Smith, 2020), or it may be reflected in the classification of simulation output using specific criteria. A question that needs to be debated is whether the modelling should focus on practical mobility (i.e., including the human factor) or whether the potential envelope of maritime mobility can be based solely on modelling the technological capabilities of the vessels.

The topic of model verification is an area where solutions are needed, with the hope of finding a standard benchmark that all modellers can use. The practice of benchmarking against historic textual evidence often lacks the knowledge of whether the reported duration was average or if it might have been a faster or slower passage. In many cases, even the season is unknown.

The topic of model output and units of measure deserves a degree of formalisation in support of sharing data and supporting downstream processes. The output of sailing duration as the single cost measure is limited in representing sailing mobility. Time spent waiting for favourable winds was common, and it is an additional cost factor. The need for a temporal dimension (monthly or seasonal) is worthy of debate.



A more detailed discussion on the methodologies of maritime movement models' inputs, processes, and outputs is presented by Slayton et al. (2025), and it is recommended reading in preparation for this session.

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| <b>14:00 – 14:20</b> | 13. The Prospects of Sharing Seafaring Modelling Data<br><i>David Gal (University of Haifa)</i> |
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| <b>14:20 – 14:40</b> | 169. Boats and (Worked) Bones: Traditional Coast Salish Social Networks and Maritime Subsistence Technologies<br><i>Adam Rorabaugh (Simon Fraser University)</i>                                                                                                                                                                                                                             |
| <b>14:40 – 15:00</b> | 198. From navigation to polar diagrams: a case study<br><i>Matteo Tomasini*</i> ; <i>Boel Bengtsson*</i> ; <i>Björn Bengtsson*</i> ; <i>Aurélien Burlot*</i> ; <i>Philippe Guillonnet (Koruc)</i> ; <i>Alvaro Montenegro (Ohio State University)</i> ; <i>Martyn Prince (University of Southampton)</i> ; <i>Frédéric Vény (Bugale Kozh Yeodet)</i><br><br><i>* University of Gothenburg</i> |
| <b>15:00 – 15:20</b> | 246. The Export Porcelain Trade Network during the Song and Yuan Dynasties: Network Modeling and Spatial Analysis Based on Multi-Source Shipwreck Data<br><i>Xinbei Song (Harbin Institute of Technology, Shenzhen)</i> ; <i>Jie He (Harbin Institute of Technology, Shenzhen)</i>                                                                                                           |
| <b>15:20 – 15:40</b> | 249. Fragmented Coasts, Connected Worlds: Maritime Interaction and Social Reorganization in the Post-Palatian Ionian-Adriatic Region<br><i>Ermioni Vereketi (NKUA &amp; University of Cologne)</i> ; <i>Eleftheria Paliou (University of Cologne)</i> ; <i>Vassilis Petrakis (NKUA)</i>                                                                                                      |
| <b>15:40 – 16:00</b> | 264. Reconstructing movement: a multidisciplinary study of ancient maritime mobility<br><i>Crystal Safadi (University of Southampton)</i>                                                                                                                                                                                                                                                    |
| <b>16:00 – 16:30</b> | Coffee break                                                                                                                                                                                                                                                                                                                                                                                 |

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| <b>16:30 – 16:50</b> | 272. Spatial Modeling Methods for Traditional Nautical Knowledge<br><i>Hongpeng Luo (Tianjin University)</i> ; <i>Jie He (Harbin Institute of Technology, Shenzhen)</i>                                                                               |
| <b>16:50 – 17:10</b> | 301. Smoothing out the Rough: A Network Analysis Approach to the Roman Colonisation of Cilicia<br><i>Adam Dawson (University of Oxford)</i>                                                                                                           |
| <b>17:10 – 17:30</b> | 307. Identifying Coastal Nodes in the Ancient Mediterranean<br><i>Karl Smith (University of Oxford)</i>                                                                                                                                               |
| <b>17:30 – 17:50</b> | 423. HUGASEA: an Agent-based Model to evaluate the interplay between Seascape, Watercraft and Human decisions (and uncertainty) on the rugged coastlines of the Pacific Americas<br><i>Alberto Garcia-Piquer (Autonomous University of Barcelona)</i> |
| <b>17:50 – 18:10</b> | Discussion                                                                                                                                                                                                                                            |

### 13. The Prospects of Sharing Seafaring Modelling Data

*David Gal (University of Haifa)*

Over the past decade and a half, studies of seafaring have begun to utilise computer models as part of their methodological arsenal. This has been facilitated by the increased use of GIS in archaeology, supported by guides that help adapt terrestrial GIS for modelling maritime movement. However, in each case, the researchers have been obliged to conduct their modelling in-house. This involves obtaining and preparing environmental data for the

study context, setting up computing resources, including automation scripts, selecting model methods and parameters, validating the model, and finally running the model to extract data. The entire process entails a slow learning curve, and the required effort may be prohibitive for many studies involving maritime movement analysis.

This paper explores the prospect of sharing seafaring modelling data to avoid the costs of in-house modelling and to increase the availability of modelling to a broader spectrum of maritime research. The examination is conducted bottom-up, first identifying the use cases and then specifying the required mobility measures. Finally, investigate possible methods for sharing mobility data, including an example mobility data repository.

Use cases can be categorised into two general categories. The first is the need to provide measures of maritime mobility to downstream quantitative processes, such as network analyses or economic models. The second use case involves analysing movement in seascapes to illuminate the characteristics of the inter- and intra-regional maritime links and the effects of mobility on other elements of the seascape.

The use cases of maritime network analysis or economic modelling require inputs of measures that reflect the cost of conducting a maritime link. This raises the question of which measures are needed to determine the costs of maritime links. Sailing speed and resulting passage duration are commonly used, but they provide a poor representation of link cost when used alone. Time spent waiting to sail may often exceed the time spent at sea and should be considered. More importantly, the probability of conducting a practical passage may vary significantly from one month to another, and this should be accounted for in cost estimation. Clearly, a temporal dimension, such as a month of the year or a season, is also necessary. In seascape movement analysis, in addition to link costs, least-cost path data are needed to indicate potential routing options. Model outputs of environmental characteristics can also support the analysis of seascapes.

Several optional routes are available for sharing modelling outputs. The first, and more basic, approach is to outsource the work to an existing modeller and toolkit through collaboration. This has the advantage of employing established knowledge without being inhibited by a shallow learning curve. The second possible solution may be achieved using interactive tools that provide transportation cost information in real time. The Stanford University Geospatial Network Model of the Roman World, ORBIS, is a good example of an interactive tool that combines both sea and land transport systems. This tool provides ad hoc responses but subsequently suffers from limited modelling accuracy in maritime transportation costs.

The third path to facilitate data sharing is the reuse of data from previously modelled maritime links. Fortunately, the period specificity of merchant ships rigged with a single-masted square sail is low, spanning from the Middle Bronze Age to the Islamic period. This spans more than two millennia during which there were no significant technological changes in ships' sailing characteristics. This attribute helps justify the reuse of data. An obvious prerequisite is that compilations of shared data should include a sufficient number of modelled passages to fulfil most, if not all, user needs.

This paper concludes with a call to modellers and users of potential sailing mobility data to jointly advance formalisation of model output measures. Agreement on the definition and prioritisation of model output measures will incentivise both the creation and utilisation of atlases of potential sailing mobility. It will also influence and improve the quality of future models.

## 169. Boats and (Worked) Bones: Traditional Coast Salish Social Networks and Maritime Subsistence Technologies

*Adam Rorabaugh (Simon Fraser University)*

In the Salish Sea of Northwestern North America, maritime travel was central to social identity, connectedness, political life, trade, and maritime subsistence. This study examines the social signals shared through maritime social networks of one set of maritime subsistence tools, bone and antler fish hooks, leisters, spears, and harpoons. The production of these technologies reflect affinal social networks of knowledge production, specifically craft and subsistence skill training.

Social network analysis is employed examining barb styles from dated site components over the mid Holocene. Dated contexts were organized by 500-year periods mitigates plateaus in regional radiocarbon curves from 2200 to 2460 BP as well as uncertainties surrounding local marine reservoir corrections for marine shell dates. Variable bin sizes and temporal breaks were assessed to confirm robustness. In addition, site components mitigate time-averaging effects given that many sites examined in this study have occupations spanning thousands of years. Four contemporaneous social networks were constructed to examine change through time (1000–1500 cal BP, 2000–2500 cal BP, 3000–3500 cal BP, 3500–4000 cal BP).

Each network node consists of bone tool assemblages from dated site components in the Salish Sea. Each node is geospatially mapped in a GIS. Edges were based on pairwise Brainerd-Robinson coefficients of the paradigmatic classes of barb styles, which represent intentional, learned, stylistic elements.

Results were converted to a cost matrix in a GIS, and the outdegree centrality statistic was used to assess the centrality of each network node based on the summed weights of all outbound edges of a node. For network comparisons,

the standardized form of the outdegree centrality statistic was used, which divided the summed outbound edge weights of a node by the sum total of all edge weights in a given network. For cross-comparison of time period networks, Kruskal-Wallis tests and Spearman's R were used to determine if there were significant differences by period or correlation with geodesic distance.

Geodesic distance not being correlated with Brainerd-Robinson coefficients has been observed with other material culture types in the Salish Sea including hafted biface styles and labrets, suggesting watercraft and seafaring mobility played a significant role in forming networks over the Holocene. This same pattern appears to hold with barbed bone tool styles.

Barbed bone tools embody a form of guarded knowledge and embedded craft specialization. Shifts through time in these networks are consistent with the traditional bilateral descent patterns of Coast Salish speaking peoples. The elaboration of these networks over the early to mid Holocene suggests cultural continuity in kinship practices since time immemorial as a result of the mobility granted by seafaring.

## 198. From navigation to polar diagrams: a case study

*Matteo Tomasini (University of Gothenburg)*

*Boel Bengtsson (University of Gothenburg)*

*Björn Bengtsson (University of Gothenburg)*

*Aurélien Burlot (University of Gothenburg)*

*Philippe Guillonnet (Koruc)*

*Alvaro Montenegro (Ohio State University)*

*Martyn Prince (University of Southampton)*

*Frédéric Vény (Bugale Kozh Yeodet)*

Modelling seafaring is a multi-scale endeavor that requires a plethora of data types and inputs. While some methods make use of large scale approaches using environmental data - such as GIS cost surface analysis tools - others attempt modelling from an agent-based perspective, trying to model micro processes such as boat-environment interactions, navigation technique and sailors' decisions (Slayton et al. 2025). The agent-based approach allows one to understand intuitively what one is trying to model: the rules of interaction of each agent are of immediate grasp, and the resulting behavior can be verified by modulating such rules in a simulation. If we assume a boat to be an agent in such a system, in principle it is enough to determine how the boat will interact with the environment (e.g. currents, winds and waves) to derive how long or how feasible a trajectory from A to B may be. In this context, a polar diagram is a piece of data determining how the vessel will interact with wind speed; the tool is mostly used for sail boats but it can also be used to assess paddling or rowing speed.

To make a high quality assessment of how a boat interacts with its environment, experimental tests need to be performed on the boat of interest. Of course, for prehistoric vessels, it is difficult to come across such high quality performance data since very often we lack the possibility to actually test archaeological remains. Thus, we need to do experiments on reproductions to

create a polar diagram. One way is to test the boat in many different situations and re-create the polar diagram directly (e.g. Gal et al. 2021). Another way is to generate a naval engineering model of the boat, and then use a few navigational results to fine tune the parameters of the model that regulate the performance profile (e.g. Bengtsson et al. 2025). This second way is particularly useful for smaller vessels whose navigation at high sea presents a substantial risk, and thus for which experimentation in many different environmental conditions may be unfeasible.

In this presentation, we illustrate the whole process to generate a polar diagram for a hide boat, using experimental data. The data included a 3D model of the boat, measurements of drag resistance, cruising speed, paddling frequency, as well as local environmental data. The data was collected during seven days of navigation experiments performed on the Léguer river estuary (west of Le Yaudet promontory) and on the Aber Wrac'h at Landéda (Finistère), with the help of a local association which builds prehistoric boats reproductions. In particular, we will focus on the difficulties and the pitfalls of such an exercise, and will look in particular at how the modelling community can benefit from engaging with citizen science associations.

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## 246. The Export Porcelain Trade Network during the Song and Yuan Dynasties: Network Modeling and Spatial Analysis Based on Multi-Source Shipwreck Data

*Xinbei Song (Harbin Institute of Technology, Shenzhen)*

*Jie He (Harbin Institute of Technology, Shenzhen)*

### Abstract

During the Song and Yuan dynasties (10th–14th centuries) of China, the Maritime Silk Road witnessed robust growth, facilitating the formation of a trans-Eurasian maritime network. Against this backdrop, Chinese export porcelain, which was produced specifically for overseas markets, emerged as a core commodity within this trading system and a key material symbol of maritime East–West exchange (So 1997). Both Mikami Tsugio’s concept of the “Ceramic Road” (Mikami 1969) and Misugi Takatoshi’s research on the “Maritime Silk Road” (Misugi 1968) used ceramic trade and cultural interaction as a lens to outline these ancient maritime corridors linking East and West.

Scattered across these sea routes, ancient shipwrecks provide tangible evidence for such macro-narratives. Ceramics recovered from these sites serve as key material evidence, offering an important research pathway for reconstructing historical trade networks. Data revealed through underwater archaeology hold significant potential: they are not merely records of isolated artifacts, but through systematic integration, they can illuminate the composition of trade goods, scale of transport, circulation routes, and market distribution of kiln products. Collectively, they form a detailed spatiotemporal database crucial for understanding the broader trade system's operation.

However, existing studies often remain confined to case analyses of individual shipwrecks, lacking systematic integration and quantitative analysis of materials from multiple wrecks across different maritime regions. As a result, they fall short of fully revealing the intrinsic connections among “shipwrecks–ceramics–kilns,” and struggle to elucidate the spatial structure and operational mechanisms of the export porcelain trade network. In this context, computational archaeology offers an effective tool to address these challenges. It not only provides a macro-level perspective for multi-shipwreck research but also, through quantitative analysis, enables in-depth exploration of the hidden trade connections and dynamic mechanisms embedded within complex datasets.

This study addresses the following core questions: How can an effective analytical framework be constructed to integrate and compare multi-shipwreck data across different maritime zones? Within this framework, what are the relationships between “shipwrecks–ceramics–kilns”? How did these relationships shape the Song-Yuan export porcelain trade network? What were the spatial structure and operational characteristics of this trade network?

To address these questions, this research adopts a computational archaeology framework, centering on the integrated application of Social Network Analysis (SNA) and Geographic Information Systems (GIS). This study focuses on shipwreck remains from the Song and Yuan periods located in the coastal waters of southeastern China and the Southeast Asian seas (partially extending to South and Northeast Asia), with export porcelain as the core material. The research materials comprise archaeological reports of shipwrecks, maps of maritime trade routes, relevant books, and historical documents. Based on these multi-source materials, information was extracted, and 35 shipwreck sites were preliminarily selected. These were linked to 12 ceramic types and 26 inland kilns, while integrating geographical spatial data and trade route information to form a comprehensive shipwreck dataset centered on export porcelain. Subsequently, network analysis was applied to the three entities (shipwrecks, ceramics, kilns), constructing both one-mode and



two-mode networks from the perspectives of homogeneous and heterogeneous objects. By calculating network metrics, key nodes and critical supply linkages were algorithmically identified. GIS spatial analysis was then employed to georeference these relational networks, enabling the modeling and visualization of geographical patterns shaped by kiln locations, maritime routes, and overseas markets. This combined computational methodology facilitates a structured research pathway: "data integration–relationship modeling–spatial mapping–cognitive advancement."

Preliminary results, derived from network metrics and spatial modeling, reveal a tightly structured, multi-layered export porcelain trade system. Moving beyond traditional typology, the core structure and nodes of the trade were clarified: the core ceramic categories were bluish white ware, celadon, and brown-glazed ware; key kilns included Longquan, Jingdezhen, and Cizao; shipwrecks are concentrated along the East Asia-Southeast Asia routes, while kilns clustered in southeastern coastal China, with the distance from kilns to ports identified as a key constraining factor. The trade network consisted of multiple regional circles, exhibiting characteristics of zonal differentiation: a "Southeast Asian diverse mixed-loading circuit" was characterized by high cargo diversity, whereas a "Northeast Asian dedicated supply circuit" was associated with fewer ceramic types and kilns. For instance, Southeast Asia demonstrates a radial "diverse mixed-loading" pattern, while Northeast Asia exhibits a linear "dedicated supply" pattern. Furthermore, network analysis highlights the prominence of the Fujian Luodong kiln, suggesting it may have functioned not only as a production center but also as a hub for regional technological exchange.

In summary, this study elucidates the core components, multi-level chains, and spatial organization patterns of the porcelain trade by identifying differentiated regional trade circles, distance-constrained trade linkages, and core hubs. The findings not only deepen the understanding of the operational mechanisms of ancient maritime ceramic trade but also provide new perspectives and a replicable quantitative model for exploring cross-regional

economic and cultural connections through the lens of material flows and spatial structures. Future research will expand on this approach, focusing on aspects such as the existence and nature of regional trade circles, kiln-port relationships, and the technological and cultural motivations behind ceramic assemblages, thereby offering more multidimensional insights for a comprehensive understanding of ancient maritime trade systems.

#### Keywords

Export Porcelain, Shipwreck, Social Network Analysis, Spatial Analysis

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## 249. Fragmented Coasts, Connected Worlds: Maritime Interaction and Social Reorganization in the Post-Palatial Ionian-Adriatic Region

*Ermioni Vereketi (NKUA & University of Cologne)*

*Eleftheria Paliou (University of Cologne)*

*Vassilis Petrakis (NKUA)*

The collapse of the Mycenaean palatial system in c. 1200 BC marked a crucial rupture in certain long-established political and economic networks of the Aegean. Yet archaeological and material evidence from western Greece, the Ionian Islands, southern Albania and the opposite Italian coasts suggest not isolation, but continued, adaptive contact (Moschos 2009). During Late Helladic IIIC and Submycenaean times, sites in Western Greece and the Ionian Islands show signs of demographic stability and concentrations of wealth. The occurrence of richly furnished "warrior" burials, imported prestige items, and locally produced items with external influences shows that maritime communication remained at the center of the survival and reorganization in some of these communities. This paper, as part of my ongoing dissertation, discusses the structure, range, and importance of such interactions along the Ionian–Adriatic corridor in the period following the destruction of the palatial centers.

Our starting point is that connectivity in the 12th century BC was not simply a trace of earlier palatial systems but an adaptive mechanism through which certain communities repositioned themselves within the post-palatial landscape. Building on recent network-based studies of Italo-Aegean interaction (van den Berg 2018), we focus on western Greece as an active interface between the Aegean and southern Italy and include the Albanian coast as a key but underexplored segment of this maritime corridor. The dataset includes approximately 110 coastal and near-coastal sites distributed across our study area. Through the combination of archaeological synthesis and computational modeling, we seek to evaluate whether these connections represent

a residual survival of Bronze Age mobility or the formation of new, decentralized exchange systems.

Methodologically, this study models and analyzes maritime connection using a sequential computational approach. First, we simulate sailing times from coastal sites (nodes) under various wind and current conditions using GIS-based marine isochrone modeling, which is implemented in ArcGIS Pro software (Di Piazza 2014). In order to define a potential interaction network, connections (edges) between these nodes are generated based on calculated travel-time intervals (e.g., one-day trip) rather than simple distance. Consequently, the network analysis component employs clustering and centrality measures to provide quantitative assessments of which sites may have functioned as intermediaries, terminals, or isolated actors within the maritime system. The paper aims to identify high-access nodes in the Ionian–Southern Adriatic seascape. These models compare archaeological distribution of LH IIIC settlements, imported material, and elite tombs in Western Greece, southern Albania, and southern Italy. The combination of environmental and archaeological datasets allows us to evaluate the extent to which environmental affordances shaped but did not determine, post-palatial mobility geography. This computational approach makes it possible to evaluate the form of interaction, by testing whether observed connectivity was centralized, distributed, or episodic, further than the simple mapping of contact zones.

Preliminary results identify a cluster of sites within the central Ionian Islands that occupy positions of high accessibility in the modeled sea-faring landscape. These nodes coincide with locales exhibiting archaeological indications of LH IIIC prosperity and social reorganization, like Ithaca's "warrior" grave and the tumuli with rich furnishings on Meganissi. The overlap between modeled accessibility and archaeological indicators of wealth and social display suggests that political or economic status may have been closely related to spatial position in the maritime system.

The pattern that emerges, however, does not suggest a single, integrated network. Instead, it suggests a fragmented, possibly decentralized set of small-scale nodes with locally restricted connections extending across the

sea. In this network, Achaea, known for its richly furnished LH IIIC burials with concentrations of imported goods, appears to function less as a hub and more as a terminal node. A place where foreign material and external influences were received, reinterpreted, and disseminated in local systems of exchange and display. Extending the analysis into the southwestern Peloponnese allows us to examine where the density of imported goods decreases, marking a potential boundary in the realm of Ionian–Adriatic interaction. In western Greece and the central Ionian Islands, selective external contacts maintained throughout a politically decentralized period can indicate that maritime connectivity itself constituted a main mechanism of social differentiation and community resilience. On the Adriatic side, evidence for the local production of Aegean-type pottery and the selective adoption of metallurgy expertise testifies to bidirectional exchange rather than unidirectional transmission. Such cross-cultural exchanges challenge traditional boundaries between "Aegean" and "Italian" material worlds and demand an integrated reading of the Ionian–Adriatic as a dynamic contact zone in negotiation. An integration of GIS modeling through isochrones and network analysis transcends static consideration of diffusion of culture or trade routes by instead addressing relational dynamics between mobility, patterns of interaction and control over resources. The study evaluates whether modeled maritime accessibility, derived from isochrone ranges, corresponds with archaeological indicators of prestige goods gathering, in order to assess whether spatial centrality within the network correlates with regional economic or political significance. In addition to reconstructing routes, the research addresses more general issues of continuity, adaptation, and resilience in post-palatial societies. It examines whether such connections are remnants of former systems or emergent, locally organized processes, and how patterns of interaction-built identities during a time of systemic change. Joining together environmental affordances and individual decision-making, the project develops an extended model of Ionian–Adriatic connectivity, illustrating how groups negotiated mobility and exchange in the absence of centralized authority. This approach situates the western Greek coast within a wider

network of interaction and highlights it as a zone of adaptability and social transformation in the aftermath of the palatial collapse.

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## 264. Reconstructing movement: a multidisciplinary study of ancient maritime mobility

*Crystal Safadi (University of Southampton)*

This paper presents a multidisciplinary approach to understanding ancient mobility, using Kyrenia Liberty, a full-scale reconstruction of the 4th-century BC Kyrenia shipwreck, as a lens through which such an approach can be explored. Drawing together experimental, digital, and analytical perspectives, the study reflects on how reconstruction, performance testing, and simulation together reshape our interpretations of ancient seafaring practice.

The paper will share new results and insights from Kyrenia Liberty's 2023 experimental voyage which was undertaken as part of the ongoing Eastern Mediterranean Experimental Seafaring project (University of Southampton, supported by the Honor Frost Foundation), as well as subsequent digital modelling and recent water tank testing. These complementary investigations reveal how variations in hull geometry, ballast configuration, and environmental exposure affect the vessel's stability and handling.

More broadly, the study argues that the integration of experimental sailing, digital reconstruction, and controlled hydrodynamic testing allows us to move beyond static reconstructions of ship design toward a dynamic understanding of mobility as practice. The Kyrenia case demonstrates how performance, material behaviour, and embodied experience intersect to inform interpretations of maritime movement in antiquity as well as its reception and interpretation in the present.

## 272. Spatial Modeling Methods for Traditional Nautical Knowledge

*Hongpeng Luo (Tianjin University)*

*Jie He (Harbin Institute of Technology, Shenzhen)*

Since the emergence of post-processual archaeology, the agency of individuals has been recognized as crucial in the construction of history. Over the nearly forty years since Ian Hodder's *Reading the Past* was published, concepts such as Human-Environment Interaction and Cultural Landscape have profoundly reshaped academic discourse. Across disciplines, scholars have increasingly reconsidered the role of humans within Space, emphasizing cognition, practice as central factors in shaping historical processes. Since its introduction in 1978, the concept of the Maritime Cultural Landscape (Westerdahl 2012) has been repeatedly highlighted by UNESCO as a catalyst for paradigm shifts in maritime archaeology and related interdisciplinary fields, providing a theoretical foundation for exploring human-sea interactions.

In recent years, maritime modeling has employed a range of computational methods to evaluate human seafaring mobility. Broadly speaking, these approaches share three core concerns: environment, technology, and human behavior (Slayton et al. 2025). However, while Technology and Knowledge are recognized as critical elements shaping Navigators' Decisions, current models still lack effective ways to incorporate these qualitative factors into spatial simulations. Therefore, this study seeks to address the following questions: (1) How can traditional seafaring techniques be identified? (2) What kind of knowledge structures do they embody? (3) How does such knowledge inform navigational decision-making? (4) And can the spatial features generated by these models reflect the authentic characteristics of maritime cultural landscapes?

Drawing upon multiple data sources, including wind data, textual records, remote sensing, and UAV-based 3D scanning. The research develops a methodological framework integrating (1) knowledge extraction from non-spatial data, (2) ontology construction through knowledge graphs, (3) and GIS-based spatial analysis. Texts such as the *ZhenluBu* 针路簿 and *GengluBu* 更路簿, which record sailing technology across the western Pacific, Southeast Asia, and the Indian Ocean, serve as key sources for modeling traditional seafaring knowledge. The goal is to visualize the Spatial-Knowledge structure of maritime cultural landscapes.

The methodology comprises three stages. (1) Knowledge Modeling. Exploration of the structure of knowledge reflects human technology (Kuhn and Hacking 2012). (a) Text Recognition and Extraction. Traditional navigation texts are processed through a locally deployed LLMs for text identification, proofreading, punctuation, and translation. (b) Structured and Relational Data Building. Digitized texts are structured into thematic vocabularies: Spatial (place names, directions, distances), Temporal (hours, months, seasons), and Environmental (depths, reefs, winds, tides, celestial angles). (c) Knowledge Graph Construction. Semantic nodes (wind direction, route, safe

harbor, place name, season) and logical edges (dependent on, suitable for, avoid) are established using triplets such as Origin-Distance-Destination, Direction-Reef-Avoidance, or Direction-Shallow-Detour, thus formalizing a computational model of traditional navigation knowledge. (2) Experience-Based Spatial Modeling. (a) Place-Name Georeferencing. Using the spatial vocabulary, place names are geocoded and visualized in GIS (figure). (b) GeoKG. Entities, relationships, and reasoning processes from the knowledge graph are mapped into spatial dimensions. (c) Experience-Based Navigation Model. Selected case studies integrate knowledge, experience, and rules onto a Least-Cost Path framework to reconstruct ancient maritime routes through iterative analysis. (3) Model Verification. Reconstructed digital routes are cross-validated against historical texts and real-world geography to confirm their feasibility, such as intelligent detours, coastal navigation, and decision-making behaviors.

Ultimately, this research links knowledge modeling with spatial simulation, incorporating experiential human decision-making logic into computational models. Academically, it seeks to transcend the conventional framework of maritime modeling by integrating cross-cultural seafaring cognition with spatial analysis. Methodologically, it establishes a cognitive and experience-based GIS model, offering a concrete pathway for combining Agent-Based Modeling (ABM) with GIS. Practically, as computational maritime modeling demands new paradigms and traditional nautical texts await structured representation, this study translates historical experiential systems into computable data structures, contributing to future research in historical geography, spatial humanities, and maritime cultural studies.

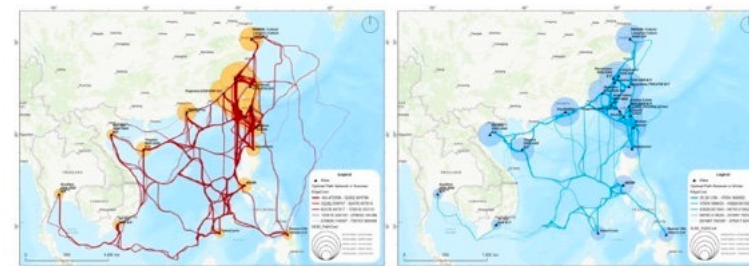


Figure. Network analysis based on geographic coordinates, wind environments.

### 301. Smoothing out the Rough: A Network Analysis Approach to the Roman Colonisation of Cilicia

*Adam Dawson (University of Oxford)*

#### Introduction

This paper is an exploratory analysis of the data collected during the Rough Cilicia survey project, undertaken to investigate the changing maritime links in Cilicia during the Hellenistic and Roman periods. During this time Cilicia experienced considerable flux transitioning from a frontier region of Alexander's empire, to a pirate haven, before becoming a specialist production area of the Roman Empire. However, until recently, data analysis has been modest. By visualising the relationships between Cilician settlements through their Brainerd-Robinson coefficients, this paper shows how Cilician transitions from being dominated Isaurian highlands with maritime connections in the Eastern Mediterranean, to a Roman colony specialising in raisin wine. The deterioration of these connections in the Late Roman period, then are used as a proxy for the decline of maritime connectivity in this period. Through this analysis this paper aims to explore, how social network analysis can be used as a proxy to model maritime connectivity through coastal survey data. These results are derived from data collected as part of the Rough Cilicia Survey Project (1996-2011). During this survey 9,709 ceramics were

catalogued throughout the coastal, semi-coastal, and hinterland areas of Rough Cilicia.

#### Methods and State of the Art

Dawson & Rauh (2025) use a combination of least-cost-paths and covert spaces analysis to suggest that during Cilicia 'pirate' era (c.144-68 BC), the region was dominated by hinterland Isaurian tribes who periodically used coastal areas to launch pirate raids. Their work noted that there was a strong correlation between covert areas and Hellenistic ceramic material. This paper looks to develop that work to see if noticeable trends between settlements are decipherable. This is attempted through creating visualisations based on sites Brainerd-Robinson coefficient, which measures the relative similarity of assemblages between two sites. A matrix of these scores can then be used to visualise the connections of all settlements within the matrix. BR scores range from 200 (assemblages are identical) to 0 (no similarity whatsoever). Golitko et al. (2012) used this method to demonstrate how Maya societies transitioned from an inland to coastal supply of obsidian between the Classic and Postclassic periods. Brughmans later developed this method to study the spread of Eastern Sigillata throughout the Mediterranean in the Roman era. This paper displays two separate visualisations for each period, that use different methods for thresholding. One uses a fixed threshold value à la Golitko et al. another using a flexible threshold based on each individual coefficient's quartile range, à la Brughmans. Cilician links between settlements are weighted by their BR coefficients, identified on the graphs by darkened colourisation, whereas external links, such as those between Hellenistic Cilicia and the Levant, are taken as binary due to a lack of information on Levantine assemblages.

#### Results

For the Hellenistic period, the fixed and upper-quartile thresholds were identical so only one visualisation was necessary. Connections were uncommon with no coastal links. However, the links that did occur indicated a very high similarity between sites. These links were between semi-coastal sites

with high covert scores (indicative of affordability for piracy), and hinterland Isaurian settlements. This complements the early ideas suggested by Dawson & Rauh that Cilician pirates were principally based further upland to avoid detection, with coastal sites being comparatively underdeveloped. Settlements are characterised by a majority of Cilician Hellenistic fineware (66-75%) and a minority of imported amphorae. The beginning of Cilicia's pirate period also sees Cilician Hellenistic fineware begin to appear in the Levant. This potentially supports Strabo's assertion that Cilician raids were organised by the Seleucid pretender Diodotus to support his coup. Alternatively, it could support de Souza's assertion that Rome's key issue in Cilicia was not piracy, but instead was that they were engaging in trade with their competitors. Here, maritime connectivity appears to link between bases with a high affordance for piracy, and the areas targeted by Cilician pirates.

For the Early Roman period both fixed and upper quartile thresholds indicate the same trend. The Roman period indicates far more connectivity. Inter-coastal connectivity is far more prevalent with most coastal settlements being linked to at least one other coastal settlement. Conversely, hinterland connections are far weaker, likely because of repeated Roman campaigns against the Isaurians led by Vatia and Pompey. Threshold scores are more varied than the Hellenistic period, with proportionally more weaker connections than previously. In terms of material, connected sites are overwhelmingly united by similar concentrations (50-60%) of Zemer 41 amphora. These amphorae were mainly used for storing wine, likely raisin wine which Strabo mentions was a speciality of Cilicia in Roman times. Here it appears that following Roman colonisation the landscape of Cilicia was transformed substantially. Links to the hinterland are suppressed in favour of specialised production and export of raisin wine.

Fixed and quartile thresholds differ substantially for the Late Roman period. Fixed thresholds produce a visualisation like that of the Hellenistic period, with a few strong links between hinterland and semi-coastal sites, but little to no coastal connectivity. However, upper quartile is far more reminiscent



of the Early Roman period, with many inter-coastal links. These trends are likely representative of the decline of Roman maritime connectivity as the Mediterranean empire weakened.

#### Discussion

A graph theory approach to changing patterns of connectivity in Rough Cilicia supports the idea that the region was controlled by the Isaurians prior to Roman colonisation. It further provides evidence for the maritime activities during the 'pirate' era by linking material present in Isaurian settlements with regions known to be raided by Cilician pirates. A development of this research should consider to what extent this material is indicative of raiding, or whether this historical suggestion is Roman propaganda designed to justify their colonisation of Cilicia and subsequent domination of the Mediterranean. The study also demonstrates the ways in which Rough Cilicia was transformed in this era, as the coasts became more connected and better populated, with an economic focus on the production of raisin wine.

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Golitko, M. Meierhoff, J. Feinman, G. Williams, P. 2012. "Complexities of Collapse: The Evidence of Maya Obsidian as Revealed by Social Network Graphical Analysis" Antiquity. vol. 86 pp. 507-523

### 307. Identifying Coastal Nodes in the Ancient Mediterranean

*Karl Smith (University of Oxford)*

This paper describes the results of a GIS analysis designed to create a set of departure and arrival points for simulated voyages as part of The Practical

Mariner project. The Practical Mariner project focusses on maritime contacts and the reconstruction of long-distance trade networks after the Late Bronze / Early Iron Age transition in the Mediterranean. One of our main research questions concerns short-haul voyages along coastlines, specifically: where did coastal mariners choose to land, and what did they base those decisions on? The analysis described here is intended to address these questions, and to inform future simulations of maritime movement.

One of the first steps in setting up maritime movement models is selecting points for simulated voyagers to start, stop, and finally finish their journeys. For journeys between a few known ports this is not a problem, but when journeys from 'coast A' to 'coast B' are considered then the researcher must come up with some way of apportioning nodes along either coast. Depending on the area under consideration, there may be several ways to do this, for example: by consulting historical records or accounts, by referencing archaeological evidence like port structures, or by using modern coastal pilots as a basis. All three of these methods are problematic when constructing a computational model. Historical records may be absent in some areas, or may be biased for or against certain activities or areas. Direct archaeological evidence for seafaring may also be difficult to detect where seafarers did not construct port facilities or modify the landscape to facilitate navigation. On the other hand, modern coastal guides and datasets reflect modern coastline changes like the draining of coastal lagoons, the construction of artificial harbours and berms, and infilling in urban areas.

In the context of the Bronze/Iron Age Mediterranean, while there is a great deal of later historical material about sailed routes, these accounts tend to focus on established shipping routes and not on petit cabotage (see Arnaud, 2020). Archaeological maps and databases such as the Ancient Ports / Ports Antiques catalogue can provide useful data, but is also limited by the availability of archaeological and topographic data and should not be used uncritically. And while a great deal of modern navigational data exists for the Mediterranean, it tends to be housed in regional or national databases which are difficult to harmonise – where data exists. The heavy modification of

Mediterranean coastlines to provide infrastructure for shipping, travel, and resource extraction also makes these datasets difficult to deal with, so that a researcher setting up a maritime-movement model may skip over good harbours on the basis that those areas are now heavily-modified ports.

A sensible option is to adopt a rubric along the lines of Wilkes (2007), who created a list of archaeological, meteorological, hydrographic, and topographic criteria in order to identify Iron Age coastal nodes along the southern coast of England, combining desk-based assessment with targeted fieldwork (see also Bradley et al., 2016). Unfortunately, a detailed desk-based assessment of the entire Mediterranean littoral is not feasible within the scope of The Practical Mariner project. Instead, we turn to GIS as a means of creating sets of plausible coastal nodes consistently from a range of environmental data sources based on different sets of assumptions about what ancient mariners could have looked for in an anchorage or a harbour. This includes shelter from wind and weather (during different years or seasons), access to food and fresh water, the availability of materials like cordage and timber for re-supply, the visibility of landmarks, the presence of nearby people and the potential for trade, and the movements of fish and birds.

Some of these factors can be represented simply by referencing (or modifying) static datasets. For example, calculating fetch (the distance wind travels over water, creating waves) can be done easily by constructing radial arrays in a grid, clipping those arrays to features representing landforms, and measuring the average length of rays in each clipped array. Modern piers and docks can be clipped out of features representing the coastline. Factors that are dynamic, like wind, fish, certain crops, and sea-level change require more sophisticated techniques to be incorporated into a model. In the first place, we continue to develop scripts to read and process multidimensional weather data in NetCDF formats into rasters suitable for GIS models, building on work presented at last years' CAA in Athens. We also incorporate simple predictive models for the movement of fish into our analysis, in order to address the hypothesis that these movements facilitated contact between

different fishing communities. In terms of resources, we combine selected satellite-derived agricultural data with desk-based economic assessments to estimate areas along the coast where people would have been able to gather sufficient materials to build or refit a ship.

We use a simple weighted-overlay model to combine these data sources, calibrating our weights based on detailed assessments of specific LBA/EIA harbours like Ugarit, Carthage, and Marsa Matruh. Our goal in conducting this analysis is not to produce an exhaustive catalogue of Mediterranean harbours, but to give ourselves a means to generate sets of harbours based on basic assumptions about where prehistoric mariners would have preferred to land. By incorporating multidimensional datasets we can expand these queries to include questions of resiliency and seasonality. These nodes will form the basis of a larger, Mediterranean-wide movement model, which is one of the final goals of The Practical Mariner project.

#### Works cited:

Arnaud, P. (2020) *Les Routes de la navigation antique: Itinéraires en Méditerranée et Mer Noire*. Arles: ERRANCE.

Bradley, R. et al. (2016) "Maritime Havens in Earlier Prehistoric Britain," *Proceedings of the Prehistoric Society*, 82, pp. 125–159.

Wilkes, E. (2007) "Prehistoric sea journeys and port approaches: the south coast and Poole Harbour," in V. Cummings and R. Johnston (eds.) *Prehistoric Journeys*. Oxford: Oxbow Books, pp. 121–130.

### 423. HUGASEA: an Agent-based Model to evaluate the interplay between Seascape, Watercraft and Human decisions (and uncertainty) on the rugged coastlines of the Pacific Americas

*Alberto Garcia-Piquer (Autonomous University of Barcelona)*

Studying the past of past peoples that lived in maritime and aquatic environments without including watercraft would be like studying present societies without automobiles. However, how boats were integrated into the economics and everyday life of past seafaring peoples, particularly in the case of small-scale and/or hunter-gatherer societies, has yet to be fully explored (Ames 2002). The HUGASEA project has addressed this issue by studying the interplay between watercraft, environment and social strategies in two maritime regions of the Pacific Americas, the Northwest Coast of North America and the Fuego-Patagonia archipelagos of Southernmost South America. Both regions are characterized by rugged and heterogeneous coastlines, as well as indigenous seafaring traditions that developed throughout the Holocene and endured beyond the post-contact period. Furthermore, in the case of the Northwest Coast, the historical seagoing cedar dugout -with its diversity of regional designs- has become a symbol of identity, resistance and social resilience for many Native Nations in the last decades. In Fuego-Patagonia, research and community-based efforts for recovering vernacular watercraft traditions are timidly growing over time, emphasizing the historical and social weight of this craft. Three main questions have been raised by this research: 1) How and to what extent did the type of watercraft technology used by seafarers shape the relationship they had with their landscape and seascape? 2) How did watercraft and seafaring support the settlement patterns archaeologically documented? 3) How did watercraft support the kind of social interaction that is documented in prehistoric or historical times? In summary, how was watercraft technology implemented not just as a technical innovation but in a social context within these two exceptional regions?

To answer these questions, a multi-disciplinary approach was developed, including the analysis of ethnohistoric and archaeological data and the use of computational approaches, particularly and Agent-based model (ABM) approach. The HUGASEA model is an ABM NetLogo model that simulates the movement of agents paddling a canoe across a simulated seascape (García-Piquer 2025). The primary objective of the model is to identify the most recurrent maritime routes between one or multiple source(s) and destination(s). As a result, it calculates the duration or risk (as defined by the user) of the navigations for one-way or round trips, based on the interaction between canoe/human agent and the environment. In addition, the model allows to evaluate the degree of connectivity between pairs of locations within the whole network based on the same criteria. Therefore, as most modelling approaches to seafaring, HUGASEA's model is based on path-finding algorithms, such as A\*. However, it has unique features. First of all, the analysis of rugged seascapes, characterized by local and sharp heterogeneity, requires the use of a high spatial resolution that is not achievable with global atmospheric or ocean circulation models. The HUGASEA model uses data from regional ocean circulation models, providing winds and sea currents data with a spatial resolution of 500m (Northwest Coast) and 1 km (Fuego-Patagonia), a spatial scale that depicts better the variability of the seascape that past humans faced in these environments, though still computationally viable. Second, many seafaring models have tended to focus on the duration or feasibility of migration travels and medium-to-long routes (Ames 2002). The HUGASEA model focuses on daily trips, that can range from a few hours to few days, focusing on how watercraft and maritime movement was implemented in the social context of the two regions and, thus, on the day-to-day scale of short-range movements. The effect of daily tides and the direction of the travel are expected to be key to the movement. Third, understanding past mobility requires dynamic approaches which incorporate uncertainty. Circumventing some limitations of least cost path models (Hewitt et al. 2025), which assume complete knowledge of the terrain on the part of the traveller, and a deterministic series of decisions, the HUGASEA model introduces uncertainty to explore potential movement along new -

unexpected- routes between two given locations. Finally, the parameters used by the HUGASEA model are drawn from ethnographic data, the archaeological record and hydrodynamic computations with 3d models of historical canoes used in the two regions. In this paper, the main features of the HUGASEA model will be presented and the results of its application to different scenarios of the two study regions will be evaluated, focusing on dimensions of the model such as uncertainty, the sensitivity of human- and environmental-based variables and the effect of small changes in the threshold of crucial variables like duration or risk.

Ames, K.M., 2002. Going by Boat: The Forage-Collector Continuum at Sea. In Fitzhugh B., Habu J. (Eds.) *Beyond Foraging and Collecting. Fundamental Issues in Archaeology*. Boston, MA, Springer: 19–52.

García-Piquer, A. 2025. Navigating Paradigms: Seafaring, Settlement patterns and Social interaction in Southernmost South America. In: *Negotiating Watery Worlds: Impacts and Implications of the Use of Watercraft in Small Scale Societies*, edited by A. García-Piquer, M. Fauvelle and C. Grier. University of Florida Press, Gainesville.

Hewitt, R. J., Alcaraz-Castaño, M., Hernandez, V. C., & Morley, M. W. (2025). Modelling Mobility of Hunter-Gatherer Populations: A Dynamic Simulation Approach Based on Cellular Automata. *Journal of Archaeological Method and Theory*, 32(4), 1-22.

## S37: Future Sight on Past Landscapes: Vision Foundation Models for Archeological Remote Sensing and Landscape Archaeology

*Sohini Mallick, Independent Researcher*

*Jürgen Landauer, Landauer AI Research*

*Agnes Schneider, Leiden University*

**Location:** Hörsaal 01

**Session Format:** Standard

For the last few decades, advances in artificial intelligence, particularly deep learning and computer vision have enabled new paradigms in the advancement of archaeological remote sensing and landscape archaeology. Recent advances in Vision Foundation Models (VFMs), including ChatGPT, Gemini, SAM, DINOv3, OWL-ViT, Grounding DINO and geospatial-specialized models like Prithvi, AlphaEarth and DeepAndes, are reshaping how we detect and interpret archaeological features from satellite, UAV, and LiDAR. Their ability to generalize across imagery types and perform *zero-shot* or *few-shot detection and segmentation* offers new opportunities for landscape archaeology and archaeological remote sensing, where annotated datasets remain scarce.

Building on recent work in archaeology (Abate et al., 2023; Ciccone, 2024; Landauer & Klassen, 2025) and remote sensing AI (Huo et al., 2025; Guo et al., 2025), this session invites applied and critical contributions that assess the potential of VFMs for archaeological feature detection, practical workflows and adaptations, reproducible pipelines, and shared resources. We also welcome reflections on key technical and ethical challenges, including false positives, interpretability, cultural sensitivity, and the risks of automated misrepresentation or misuse, as we collectively explore the role of

vision AI in advancing scalable, robust, and responsible archaeological research.

**Topics of Interest include but are not limited to:**

- *Model Application & Evaluation*

We are looking for case studies of using VFMs for detecting archaeological features in satellite, UAV, or LiDAR data. Topics include comparative evaluations of general-purpose and geospatial models, prompt engineering, tiling strategies, terrain classification, anomaly detection, and clustering.

- *Deployment & Field Integration*

We are interested in the integration of VFMs into field workflows through drones, edge devices (e.g., Jetson), and mobile platforms. Especially real-time detection, vision-assisted mapping, and energy-efficient or offline deployments in remote areas [Visual Perception Engine](#)

- *Benchmarks, Reproducibility & Tools*

We would like to focus especially on the development of modular pipelines, open-source tools, and well-documented workflows. We are hoping for contributions which address FAIR data practices, benchmark design, annotation formats, and archaeology-specific evaluation metrics such as IoU or false positive rates.

- *Critical Perspectives & Position Papers*

Taking a step forward, we specifically encourage conceptual and technical reflections on adapting Vision Foundation Models for archaeology. Amongst others topics such as the feasibility and value of domain-specific pretraining (e.g., an “ArchaeoVFM”), handling model failure modes such as false positives and hallucinations, and challenges in interpretability for heritage-specific outputs are of interest. Theoretical contributions that explore the epistemological implications of relying on foundation models in archaeological remote sensing and landscape archaeology are strongly welcomed.

- *Community & Collaboration*

On a broader scale, initiatives focused on shared infrastructure, participatory annotation, and interdisciplinary research are very welcome, including open benchmarks, collaborative tools, and frameworks that promote reproducibility and community engagement.

- *Ethical Implications of using Vision Foundation Models in Archaeology*

Lastly but of course not least at all, we are looking for papers which focus on the cultural and ethical responsibilities involved in the application of VFMs to archaeological data. We consider this as an umbrella for the risks of enabling looting, unauthorized site exposure, applying models without contextual knowledge, and/or reinforcing geographic and cultural bias. We encourage contributions which address how to communicate model limitations, uncertainty, and confidence in ways that are transparent and respectful of heritage contexts.

**To support transparency and reproducibility, we ask contributors to:**

- Report evaluation metrics clearly (e.g., precision, recall, IoU, false positive rates)
- Document datasets, preprocessing, and annotation workflows
- Disclose compute infrastructure (e.g., GPU specs, inference/runtime details)
- Communicate uncertainty and model limitations responsibly
- Include pipeline diagrams or summaries when applicable

**Presentation Submission Formats**

We welcome standard talks of 15 minutes and lightning talks of 5 to 10 minutes, highlighting a specific topic, idea or case study. Please indicate your preferred presentation format when submitting.

We especially encourage submissions from early-career researchers and students.

## References:

Abate, N.; Visone, F.; Sileo, M.; Danese, M.; Minervino Amodio, A.; Lasaponara, R.; Masini, N. 2023. Potential Impact of Using ChatGPT-3.5 in the Theoretical and Practical Multi-Level Approach to Open-Source Remote Sensing Archaeology, Preliminary Considerations. *Heritage*, 6, 7640-7659. DOI: <https://doi.org/10.3390/heritage6120402>

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Landauer, J., Klassen, S. 2025. Visual Foundation Models for Archaeological Remote Sensing: A Zero-Shot Approach, *MDPI Geomatics*, forthcoming. Preprint available at <https://www.preprints.org/manuscript/202508.0379/v1>

Huo, C.; Chen, K.; Zhang, S.; Wang, Z.; Yan, H.; Shen, J.; Hong, Y.; Qi, G.; Fang, H.; Wang, Z. When Remote Sensing Meets Foundation Model: A Survey and Beyond. *Remote Sens.* 2025, 17, 179. DOI: <https://doi.org/10.3390/rs17020179>

Guo, J., Zimmer-Dauphinee, J., Nieusma, J.M., Lu, S., Liu, Q., Deng, R., Cui, C., Yue, J., Lin, Y., Yao, T., Xiong, J., Zhu, J., Qu, C., Yang, Y., Wilkes, M., Wang, X., VanValkenburgh, P., Wernke, S.A., & Huo, Y. (2025). DeepAndes: A Self-Supervised Vision Foundation Model for Multi-Spectral Remote Sensing Imagery of the Andes. *Arxiv*, DOI: <https://doi.org/10.48550/arXiv.2504.20303>.

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| <b>08:30 –<br/>08:50</b> | 76. “Your Landscape Talks to You”: Making AI Accessible for Landscape Archaeology through a QGIS Plugin<br><i>Jürgen Landauer (Landauer Research)</i> |
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| <b>08:50 –<br/>09:10</b> | 90. Towards Benchmarking Vision Foundation Embeddings for Archaeological Remote Sensing : A Modular, Reproducible Pilot Using DINOv3 for Eastern India<br><i>Sohini Mallick (Barcelona Supercomputing Centre); Jürgen Landauer (Landauer Research)</i> |
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| <b>09:10 –<br/>09:30</b> | 353. Intelligent Detection of Earthen Sites in Xinjiang's Tarim Region: Leveraging Archaeological Knowledge and Multimodal LLMs with High-Resolution Imagery<br><i>Linru Xu*; Tong Liu*; Jie He*</i> |
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*\*Harbin Institute of Technology (Shenzhen)*

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| <b>09:30 –<br/>09:50</b> | 392. From Limited Labels to Scalable Survey: Leveraging Vision Foundation Models for Few-Shot Detection of Archaeological Features in Satellite Imagery<br><i>Junlin Guo*; Yuankai Huo*; James Zimmer-dauphinee*; Xiao Wang (Oak Ridge National Laboratory); Parker Vanvalkenburgh (Brown University); Steven Wernke*</i> |
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*\* Vanderbilt University*

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| <b>09:50 –<br/>10:10</b> | 420. No more training data: visual language modeling for large-scale archaeological studies in Egypt<br><i>Iban Berganzo Besga (Barcelona Supercomputing Center); Islam Kamal (University of Sadat City); Hector A. Orengo (Barcelona Supercomputing Center)</i> |
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| <b>10:10 –<br/>10:30</b> | 440. Mergin Maps: Currently the Most Optimal Solution with Advanced Functions and Easy Set-Up?<br><i>Barbora Weisssova (Czech Academy of Sciences, Prague); Katrin Dorfner (Charles University, Prague)</i> |
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| 10:30 –<br>11:00 | Coffee break |
| 11:00 –<br>11:15 | Discussion   |

## 76. “Your Landscape Talks to You”: Making AI Accessible for Landscape Archaeology through a QGIS Plugin

Jürgen Landauer (Landauer Research)

Recent developments in artificial intelligence (AI) have led to the emergence of so-called foundation models. This new class of neural networks — exemplified by systems such as ChatGPT and Google Gemini — has evolved from text-based tools into multimodal systems capable of processing not only text but also imagery. These models can perform visual question answering, identifying and describing what appears in an image and where it is located. Their capabilities have recently been extended to remote sensing data, including aerial photography, satellite imagery, and LiDAR.

In a recent study [1], we investigated whether such multimodal foundation models can recognize and interpret archaeological features in landscape datasets. Our experiments demonstrated that these systems can classify features such as barrows or enclosures, provide bounding boxes for their location, and explain their reasoning in natural language. Crucially, this approach requires no model training or dataset preparation — the so-called zero-shot property — making it exceptionally easy to use for archaeologists without a technical background.

To translate these findings into a practical tool, we have developed and are releasing LandTalk.AI (Fig. 1), an open-source QGIS plugin that integrates this AI capability directly into the GIS environment. Users can select an area on the map, submit it to the model, and receive an archaeological feature classification with spatial and interpretative feedback.

Our objective is to lower the threshold for applying artificial intelligence in archaeological research and heritage management. By embedding multimodal AI into familiar workflows, we aim to make advanced computational methods accessible to a broad community of landscape archaeologists, fostering new forms of interactive and interpretable AI-assisted analysis.

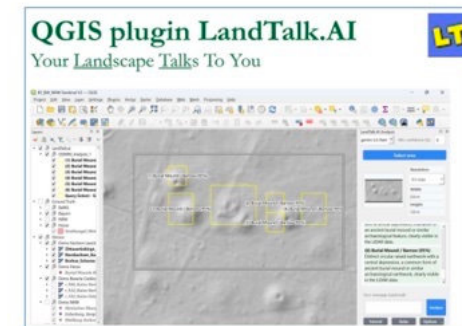


Fig. 1: QGIS Plugin LandTalk.AI

### Reference

[1] Landauer, Jürgen, and Sarah Klassen. 2025. "Visual Foundation Models for Archaeological Remote Sensing: A Zero-Shot Approach" *Geomatics* 5, no. 4: 52. <https://doi.org/10.3390/geomatics5040052>

## 90. Towards Benchmarking Vision Foundation Embeddings for Archaeological Remote Sensing : A Modular, Reproducible Pilot Using DINOv3 for Eastern India

Sohini Mallick (Barcelona Supercomputing Centre)

Jürgen Landauer (Landauer Research)

### Abstract

The introduction of vision foundation models (VFMs) has opened new directions in computer vision and remote sensing. Archaeology has only begun to engage with these advances: Landauer and Klassen (2025) recently demonstrated the potential of zero-shot, prompt-based detection for archaeological landscapes, showing how VFMs can identify sites without task-specific training. This paper proposes a **complementary step**, evaluating an **embeddings-based approach**, to explore whether pretrained visual representations capture patterns in archaeological data that can be systematically benchmarked and reused. In this pilot, we deliberately scope the problem to temple precincts in eastern India, to deliver a realistic, reproducible evaluation in the short-term, while laying groundwork for expansion to other monument types and neighboring states. Eastern India offers temple precincts with recognizable architectural signatures set in lateritic uplands and river corridors, a mix that is both archaeologically legible and remotely challenging.

In computer vision and allied fields, domain-specific benchmarking has proven crucial. In Earth observation, initiatives such as SpaceNet (Van Etten *et al.* 2018) have created shared datasets and metrics that accelerated algorithm development for building detection and mapping. In medical imaging, radiology benchmarks (Bahroon *et al.* 2023) have made it possible to evaluate representation learning across institutions and modalities. Similarly, geospatial AI research has emphasized the need for foundation models that can be assessed consistently across multispectral and topographic datasets (Huo *et al.* 2025; Guo *et al.* 2025). Archaeology currently lacks such benchmarks:

most studies remain site-specific, methods are hard to compare, and reproducibility is limited. Establishing **evaluation frameworks** for archaeological AI is therefore a necessary step if VFMs are to move beyond isolated case studies toward wider adoption. Our regional focus offers a *tractable first test* of such a framework, while retaining a clear pathway to broader coverage.



*Representative image tile from West Bengal, India used to develop the pilot embedding-based benchmark for temple precincts. Illustration only; not study results. Data Source: Google Maps.*

This paper introduces the design of a benchmarking framework for archaeological remote sensing based on DINOv3 embeddings. We focus on DINOv3 as a representative state-of-the-art self-supervised vision transformer, chosen for its strong performance in general-purpose image representation. The goal is not to test the entire range of VFMs, but to establish whether embeddings from a single powerful backbone can capture archaeologically meaningful distinctions. For this initial study, we assemble a curated, temple-focused database from openly available imagery, sufficient to assess whether generic embeddings recover recognisable architectural textures with minimal supervision.

The framework will evaluate embeddings extracted from archaeological remote sensing imagery using:

*Structure discovery*: Test whether unlabeled image tiles self-organize in representation space in ways that correspond to recognizable temple precinct patterns.

*Label-efficient recognition*: Check whether small amounts of annotation are sufficient to separate temple tiles from surrounding context, providing a realistic path for field teams with limited labels.

*Interpretability and outputs*: Generate map overlays showing clustered regions, similarity retrieval panels, and error analyses that highlight false groupings or ambiguous cases, to help archaeologists judge what the embeddings capture and where they fail.

By clustering in high-dimensional representation space, embeddings could capture recurring visual or geomorphological patterns that are difficult to specify in advance. Testing this systematically in archaeological contexts is therefore an important step toward understanding what VFMs can and cannot offer.

The contribution is twofold. First, to argue that **benchmarking embeddings** is a necessary complement to prompt-based evaluation, providing archaeologists with a baseline for reproducibility and comparability. Second, to situate archaeology within wider CV/RS debates on domain-specific evaluation, showing how benchmarks in other fields have transformed research practice. By focusing on DINOv3 embeddings as a first step, this paper aims to stimulate discussion on reproducible evaluation and to lay the groundwork for cumulative progress in archaeological applications of VFMs.

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## 353. Intelligent Detection of Earthen Sites in Xinjiang's Tarim Region: Leveraging Archaeological Knowledge and Multimodal LLMs with High-Resolution Imagery

Linru Xu (Harbin Institute of Technology, Shenzhen)

Tong Liu (Harbin Institute of Technology, Shenzhen)

Jie He (Harbin Institute of Technology, Shenzhen)

Xinjiang's Tarim, located in the heartland of the ancient Western Regions and serving as a critical convergence point of the northern and southern Silk Road routes, hosts a wealth of cultural landscapes centered on earthen sites dating from the Han–Tang periods through the Qing Dynasty. However, long-term weathering and modern agricultural activities have significantly obscured the surface features of these sites, making them blend subtly with the surrounding environment. This poses considerable challenges for traditional field surveys, which are often inefficient, unsystematic, and prone to omissions.

In recent years, increased use of remote sensing and more extensive heritage documentation in Tarim have provided large collections of aerial/satellite images and textual records, creating a valuable foundation for archaeological research. However, monitoring these vast areas and diverse site forms

remains challenging. Conventional methods relying heavily on expert input are time-consuming. Meanwhile, deep learning-based object detection algorithms (e.g., YOLO) primarily focus on image features, lacking robust generalization and semantic understanding capabilities required for identifying earthen sites with high environmental similarity and morphological variability. In this context, specialized large models that incorporate archaeological knowledge offer a key advantage here, as they can effectively combine satellite imagery, terrain data, and historical documents through visual-semantic linking for more accurate identification.

This research employs the Qwen2.5-VL-32B Multimodal Large Language Model (MLLM) to establish a "Text-Vision-Task Execution" technical framework for detecting earthen sites in the north of the Kashgar River. To address challenges such as significant morphological variation and severe weathering of sites in the region, the study undertakes the following steps: (1) Categorizing earthen sites by type, morphology, and spatial location. Geographic coordinates of sites like forts and walled towns in Xinjiang are compiled from the Third National Cultural Relics Census to build a geodatabase. Furthermore, LLM prompts are used to extract professional knowledge (e.g., location, spatial structure, chronology) from literature such as the Complete Collection of Cultural Relics and Archaeology of the Western Regions and the Survey Report on the Great Wall Resources of the Xinjiang Uygur Autonomous Region, forming attribute tables. (2) Integrating multi-source remote sensing data, including high-resolution open-source Google Earth sub-meter imagery, declassified CORONA historical imagery, and DEM data. (3) Generating structured descriptive texts by analyzing site morphological characteristics (e.g., right-angle structures, enclosed shapes, site size) and spatial relationships (e.g., proximity to ancient roads, surrounding topography), thereby constructing a "Morphological Feature-Spatial Relationship-Site Type" logical chain to create a multimodal dataset for model training. (4) Developing a multi-level site evaluation system based on archaeological knowledge, considering aspects such as site morphology, surrounding environment, and related site systems. This system employs criteria like basic dimension

evaluation, strong evidence dimension evaluation, and rank definition, and serves as the basis for designing a reasoning workflow. (5) Applying Low-Rank Adaptation (LoRA) for lightweight fine-tuning of the large model. The curated dataset is used for fine-tuning, ensuring high generalization capability on the test set and effectively improving detection confidence and robustness for weathered sites. (6) Utilizing the fine-tuned model to identify sites across various detection areas. Experiments demonstrate that the model successfully detected multiple suspected site targets with different scales, morphologies, and high confidence levels. Its precision and recall rates significantly surpassed those of traditional deep learning methods and general-purpose large models, proving the higher applicability and archaeological practical value of the proposed method in arid and semi-arid environments.

This research enhances the expert reasoning capability of multimodal large models for specific tasks through techniques like fine-tuning, prompt engineering, and structured reasoning. It validates the high efficiency of MLLMs in identifying sites within complex environments. The established "Text-Vision-Task Execution" technical framework holds significant potential for application in archaeological surveys of similar arid and semi-arid regions along the Silk Road, providing an interpretative foundation for the systematic study of earthen site cultural landscapes in Xinjiang.

### 392. From Limited Labels to Scalable Survey: Leveraging Vision Foundation Models for Few-Shot Detection of Archaeological Features in Satellite Imagery

*Junlin Guo (Vanderbilt University)*

*Yuankai Huo (Vanderbilt University)*

*James Zimmer-dauphinee (Vanderbilt University)*

*Xiao Wang (Oak Ridge National Laboratory)*

*Parker Vanvalkenburgh (Brown University)*

*Steven Wernke (Vanderbilt University)*

Research employing AI and Deep Learning for archaeological survey of satellite imagery has expanded rapidly over the past five years (e.g., Fraser et al. 2024; Kadhim and Abed 2023; Landauer and Klassen 2025; Orengo et al. 2020). However, the scale of archaeological data tends to remain relatively small by the standard of AI applications. ImageNet—perhaps the best known benchmark dataset in Computer Vision research—contains more than 14 million images. In contrast, even the most intensive satellite imagery survey projects in archaeology have tended to identify loci numbering, at most, in the 10s of thousands of features (Wernke et al. 2024)—comparable to the number of images in the small-scale computer vision dataset MNIST, which is used in introductory machine learning classes. Indeed, more typically, archaeological satellite survey data operates on the scale of dozens or hundreds of features, such as a recent publication analyzing the regional distribution of 76 Andean hunting traps (Oyaneder 2025). Of course, due to cultural and chronological variation, modeling archaeological sites in satellite data is much more challenging than distinguishing between, say, cats and dogs—or between standardized models of automobiles. As a result, we do not have sufficient data for effectively training traditional deep learning models.

A growing number of studies have shown that training AI models to recognize specific archaeological features requires large, feature-specific labeled datasets. For example, Castiello et al (2025)’s note that more than one thousand annotated examples of circular structures (“pucarás”) were required in order to train a CNN capable of reliably identifying them in the desert landscape of northern Chile. However, archaeologists are often interested in many different feature types and scales (including highly idiosyncratic feature types), which makes it impractical to create separate large annotated datasets and models for each individual feature of interest. Moreover, the lack of significant profit incentives for heritage applications means that there have been few large-scale attempts to create training data for archaeological feature detection.

Recent generalizable vision foundation models (VFMs) such as DINOv3, AlphaEarth, and DeepAndes can help us address these issues by enabling few shot and zero shot feature detection and segmentation. These VFMs are pre-trained on extensive datasets. For example, DINOv3 is trained on over 1 billion images, while our Andes-specific model DeepAndes is pretrained on more than 3 million multispectral WorldView satellite images (Guo et al. 2025). Through large-scale self-supervised learning, these models learn highly transferable visual representations that can be adapted to new feature types (e.g., archaeological loci) with minimal additional annotation. As a result, they enable few-shot and even zero-shot computer vision tasks in archaeological remote sensing, reducing the need to build a dedicated large labeled dataset for every feature of archaeological interest.

For example, archaeologists can provide a small but diverse set of example images of a particular archaeological feature. The VFM embeds these examples as anchor representations in its feature space and can then retrieve visually similar loci across large regions without additional training (i.e., in a zero-shot manner). This allows researchers to rapidly identify new and previously undocumented instances of a feature at continental scale—an

otherwise infeasible task using manual methods—and to better understand its spatial distribution and associated cultural or environmental patterns.

For few-shot detection and segmentation, the adaptable backbones (usually Vision Transformers) of VFMs can be plugged into existing, well-established computer vision frameworks. For example, by integrating these backbones into state-of-the-art detection models such as YOLO, we can enable low-resource fine-tuning and provide archaeologists with practical tools for detecting archaeological loci using bounding boxes. This makes it possible to develop effective detection systems even when only a small number of labeled examples are available. In turn, this accelerates the pace of archaeological survey, helping to reveal broader patterns of settlement, infrastructure, and cultural interaction.

Through these means, we leverage our improved VFM DeepAndes 2.0, and, together with general-purpose vision foundation models such as DINOv3, we accelerate and scale our archaeological survey of the central Andes. The examples retrieved through large-scale similarity search are then used to train feature-specific detection models, enabling the efficient and scalable identification of archaeological features such as corrals, buildings, and terracings.

## 420. No more training data: visual language modeling for large-scale archaeological studies in Egypt

*Iban Berganzo Besga (Barcelona Supercomputing Center)*

*Islam Kamal (University of Sadat City)*

*Hector A. Orengo (Barcelona Supercomputing Center)*

Emerging deep learning (DL) technologies are redefining computer vision by integrating advanced language models capable of understanding complex visual contexts. These multimodal systems bridge the gap between images

and text, allowing machines to interpret visual data with semantic awareness rather than relying solely on pixel-level patterns.

Recent research has demonstrated the ability of visual language models (VLM) to uncover new archaeological features and extract knowledge from complex visual information, creating new opportunities for automated analysis (Landauer and Klassen, 2025). However, despite substantial advancements in other areas (Van den Dikkenberg and Brandsen, 2025), their use within remote sensing remains limited. This study, together with emerging contributions in the field (Berganzo-Besga and Orengo, 2025), allows, using CLIP and GPT4.1. VLM, the detection of archaeological sites in satellite imagery such as Sentinel-2.

From zero-shot image classification to detailed scene understanding, language-enhanced vision models can achieve accuracy levels comparable to traditional CNN-based methods while eliminating the need for training data. Likewise, VLM prove essential in small-scale scenarios, such as the study area in the Nile Delta of the present study, where traditional DL models become impractical or ineffective.

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## 440. Mergin Maps: Currently the Most Optimal Solution with Advanced Functions and Easy Set-Up?

*Barbora Weissova (Czech Academy of Sciences, Prague)*

*Katrin Dorfner (Charles University, Prague)*

### Introduction

Systematic surveys, prospections, verification of legacy data, and ground control of features derived from remote sensing are common practices in archaeological research. Until recently, such activities required a complex and time-consuming preparation process – from the costly purchase and setup of data collection devices to the configuration of software and mobile applications, many of which were originally designed for entirely different purposes. In the very recent past, this process demanded at least one experienced specialist who devoted most of their time to developing, configuring, and troubleshooting the system. However, over the last decade, a wide range of field applications has emerged – more or less ready-made solutions that have gradually simplified the task of digital data recording directly in the field.

The present study builds on 15 years of field experience and evaluates various systems and applications used for data collection. It compares their complexity, available functions, cost-effectiveness, and time required for system setup.

### Methods and Materials

The case study focuses on four commonly used and easily accessible applications: Mergin Maps, QField, SW Maps, and Survey123. The experiment showing their usability was conducted with students who had a solid background in GIS and archaeological survey methods but had no prior experience with any of the aforementioned applications.

Their ability to design a functional data collection system that worked effectively in the field – including synchronizing or downloading of the data – was

observed and assessed. Instances of user frustration, as well as the causes of any failures, were also recorded and analyzed.

### Results

The case study demonstrates that Mergin Maps is the most cost-effective solution and offers the easiest access for users with limited experience. Key functions – such as installation in QGIS, account creation, basemap setup, vector layer editing in the field, and photo attachment directly linked to individual features – proved to be highly intuitive and efficient, with minimal technical issues encountered. Another important factor in ensuring good applicability is the availability of detailed application guidelines, which are either available online for free (Lutra Consulting 2025) or as a publication for a fee (Menke and Bucha Rášová 2024).

A few minor limitations were noted when using the free version of Mergin Maps. The storage space is limited, preventing the upload of large files such as satellite imagery or digital elevation models. This, however, can be easily resolved either through a modest investment in the paid version or by using online base maps.

Another small drawback is that only one photo can be attached per attribute field. While this ensures that at least one image remains permanently linked to a given feature, any additional photographic documentation must be handled separately. In most cases, this is not a major issue, as field devices used for digital recording often have only basic cameras, and photos are typically taken for easier post-processing. Nonetheless, as the quality of mobile device cameras continues to improve, this limitation could become more significant in the near future – and indeed, it was the most frequent source of frustration among the participants.

### Discussion

Despite a few minor weaknesses, Mergin Maps proved to be the most reliable and user-friendly open-source tool for the rapid collection and processing of archaeological field data. This case study aims to facilitate the adoption of

such tools by new users and to highlight potential limitations that might otherwise only become apparent during fieldwork.

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## S39: Palaeo-GIS

*Patrick Cuthbertson, The Central Asian Archaeological Landscapes (CAAL) Project, UCL; Centre for the Archaeology of Human Origins (CAHO), University of Southampton*

*Christian Sommer, Heidelberg Academy of Sciences and Humanities Research center “The Role of Culture in Early Expansions of Humans” (RO-CEEH) at the Senckenberg Institute and the University of Tübingen*

*Peny Tsakanikou, The University of Crete Research Center (UCRS), Department of History and Archaeology, University of Crete, Gallos Campus, 74150 Rethymno*

**Location:** Hörsaal 03

**Session Format:** Standard

In the first Palaeo-GIS session (CAA Tübingen, 2018) we contended that Palaeolithic and prehistoric applications of GIS are fundamentally different from applications in later periods, and advocated for particular consideration of their unique analytical challenges and ‘temptations’ (Cuthbertson & Tsakanikou 2023).

The aim of our second Palaeo-GIS session is to further develop this theme in discussion with GIS users facing similar issues in Palaeolithic and later prehistoric research contexts.

The study of human prehistory requires an holistic approach to properly assay the complex interplay of palaeoenvironmental factors, resources (affordances), material culture, and early human behaviour across vast spatio-temporal scales.

Although Geographic Information Systems (GIS) have proven an effective analytical tool for integrating and analysing these different factors and their interrelationships, a unique theoretical basis for their application is still underdeveloped.

Palaeolithic applications of GIS can be used to:

- Address prehistoric research themes at different spatial scales, from analysis of individual artefacts, the more familiar scale of the site, and over increasingly vast regions and landscapes to the continental level.
- Tackle broad, continental-scale prehistoric narratives, and even provide finer-scale empirical and analytical connection for broader scale narratives.
- Integrate time-depth through the capabilities of temporal GIS (or TGIS), to understand environmental and occupation change over time.
- Organise, analyse, and visualise archaeological and paleoenvironmental data from diverse sources; combining and compiling from diverse spatial datasets and generating novel data.
- Analyse the impact of enduring physical features on ancient human occupation, such as geomorphological, tectonic, and geological factors.
- Employ a vast array of tried and tested geospatial computational methods for data analysis, as well as including the tools to develop bespoke methods of analysis.
- The capability to generate and test predictive models, which is probably the most common current usage of GIS in Palaeolithic applications.
- The effective communication and dissemination of results through map making, georeferenced orthophotos, and other cartographic outputs.
- Make use of standardised and reusable filetypes and data schemes developed in other areas (e.g. Building Information Modelling (BIM)) for coordinated collaboration, sustainable data publication, and long-term preservation.

This potential of GIS applications in Palaeolithic and later prehistoric research has only very partially been explored, and there remains a lot of potential for innovative and bespoke solutions. The opportunity remains to develop new approaches that emerge from the needs and logical structure of Palaeolithic research and the prehistoric record, rather than being driven primarily by technological or conceptual developments in other fields.

It is a combination of the analytical challenges and temptations of Palaeolithic applications of GIS that potentially hinder the ability of researchers to capitalise on this opportunity. Our identified challenges and temptations of Palaeolithic applications of GIS are:

#### Challenges

1. poor data coverage
2. vast spatio-temporal scale
3. the difficulty of inferring behavioural patterns under the conditions of problems 1. and 2.

#### Temptations

1. to follow the data coverage, rather than to try to generate data for difficult places and periods
2. to adapt questions to the logic of data structure, rather than re-work data to suit questions
3. to do analyses that are familiar but irrelevant, rather than pioneer new methodological solutions (Cuthbertson & Tsakanikou 2023: 14).

The Palaeo-GIS session is intended to encourage contributions from authors applying GIS in Palaeolithic or later prehistoric contexts and research topics. We particularly encourage authors to submit papers that reflect on the unique characteristics and challenges of their prehistoric research context, and engage reflectively with those challenges.

## Reference:

Cuthbertson, P and Tsakanikou, P. 2023 Challenges in Palaeolithic Spatial Archaeology: Two Eurasian Case Studies. In: Human History and Digital Future : Proceedings of the 46th Annual Conference on Computer Applications and Quantitative Methods in Archaeology. 31 October 2023. Tübingen University Press. pp. 51–68. DOI: <https://doi.org/10.15496/publikation-87765>.

- 14:00 – 14:20** 81. A pre-informed end-member modelling approach to infer sediment sources and landscape evolution: an example from the Fayum Basin, Egypt  
*Annelies Koopman\**; *Willem Toonen\**; *Maarten Prins\**; *Sjoerd Kluiving\**

*\*VU Amsterdam*

- 14:20 – 14:40** 162. Lower Palaeolithic hominin activity at the Lesvos wetland: a view from agent-based modelling and affordance analysis  
*Simon Kübler (Ludwig Maximilian University of Munich)*; *Peny Tsakanikou (University of Crete)*; *Nena Galanidou (University of Crete)*

- 14:40 – 15:00** 178. Rocky Roads: Simulating Neanderthal Mobility and Lithic Resource Use in the Liguro-Provençal Arc during MIS 3  
*Amélie Vallerand (University of Montreal)*; *Claudine Gravel Miguel (New Mexico Consortium)*; *Julien Riel-Salvatore (University of Montreal)*

- 15:00 – 15:20** 253. Geospatial predictive modelling of prehistoric rock shelter sites: A case study from eastern South Africa

*Felix Weinschenk (ROCEEH/University of Tuebingen)*; *Gunther Heinz Dietrich Möller (University of Tuebingen)*; *Lawrence Msimanga (ArcheoTask)*; *Volker Hochschild (University of Tuebingen)*; *Manuel Will (University of Tuebingen)*; *Christian Sommer (ROCEEH/University of Tuebingen)*

- 15:20 – 15:40** 258. The SUGAR ecosystem: Integrating archaeological data management and GIS-driven analysis for multi-layered Pleistocene excavations

*Xavier Roda Gilabert\**; *Susana Vega Bolívar\**; *Xavier Sánchez-Martínez (IPHES-CERCA, Universitat Rovira i Virgili)*; *Sofía Samper Carro (Australian National University)*; *Jorge Martínez-Moreno\**; *Rafael Mora Torcal\**

*\*Universitat Autònoma de Barcelona*

- 15:40 – 16:00** 349. Endless desert, endless possibility - Survey planning, data collection and data storage of the ARIMAS project  
*Matthias Blessing (University of Vienna)*; *Aurore Val (CNRS)*; *Kaarina Efraim (National Museum of Windhoek)*; *Dominic Stratford (University of Witwatersrand)*; *Christian Sommer (University of Tübingen)*

- 16:00 – 16:30** Coffee break

- 16:30 – 16:50** 367. Predicting Palaeolithic Site Distribution Using MaxEnt Modelling in the Walannae Formation, South Sulawesi (Indonesia)  
*Putra MUHAMMAD (National Museum of Natural history in Paris)*; *Akin Duli (Hasanuddin University)*; *Hasanuddin Hasanuddin (National Research and*

*Innovation Agency of Indonesia); Budianto Hakim  
(Pusat Kolaborasi Riset Arkeologi Sulawesi (Collaboration Research Centre of Archaeology))*

**16:50 – 17:10** 387. Accounting for uncertainty in sea-level reconstructions using Bayesian hierarchical modelling: A case study from Mesolithic western Sweden  
*Isak Roalkvam (Aarhus University); Victor Lundström (Rio Göteborg)*

**17:10 – 17:30** 409. Settlement Development in the Okluky River Basin in the Light of Current Archaeological Evidence  
*Klára Augustinová (Archaea Olomouc); Tomáš Krampěra (University of Hradec Králové)*

**17:30 – 17:50** 442. Ecological Gradients as Sandboxes: Complexity, Environment, and Social Hierarchy  
*Chiara Girotto (LMU)*

**17:50 – 18:10** 443. Challenges and Lessons in Palaeo-GIS: Modelling Late Neolithic Movement in the Mountain Landscapes of the Eastern Rim of the Tibetan Plateau  
*Yidan Zhang (University of Oxford)*

## 81. A pre-informed end-member modelling approach to infer sediment sources and landscape evolution: an example from the Fayum Basin, Egypt

*Annelies Koopman (VU Amsterdam)*

*Willem Toonen (VU Amsterdam)*

*Maarten Prins (VU Amsterdam)*

*Sjoerd Kluiving (VU Amsterdam)*

### Introduction

End-member modelling, or statistical unmixing, applied to grain-size data is a valuable tool in sedimentology. It can reveal the sedimentary inputs to a system, which cannot be identified using univariate grain size parameters alone (Van Hateren et al. 2018, 63-64). Unmixing of grain size distributions (GSDs) entails decomposition into several representative components, connected to the internal sorting within a sedimentary system: e.g., proximal-to-distal fining trends attributable to selective transport, or to sediment dispersal from different sources and by different means of transport.

In this paper, we attempt to unlock the potential of end-member modelling (EMM) on grain size data, for geoarchaeological research in complex sedimentary settings. As a case study, we focus on the Fayum Basin, a natural depression located in northern Egypt (Fig. 1). We also demonstrate how to reach the most out of the EMM-output for studying the effects of erosion and deposition on the formation of the surface archaeological record in this erosive setting.

The Fayum Basin holds a key position in providing valuable insights on the interrelationships between regional hydroclimatic change, the flow regime of the Nile, and the role of environmental changes in prehistoric human behavior. Mobility and variable landscape use in the Fayum Basin during the Early and Middle Holocene point to the adoption of a range of socio-economic responses to deal with local environmental uncertainty and to enhance predictability (Holdaway et al. 2010). Palaeo-environmental uncertainty in the Fayum Basin needs to be understood in relation to shifts in availability of water in the depression, impacting local flora and associated local fauna, and human use of resources in the past (Phillipps et al. 2016).

However, the lack of consensus on the spatial and temporal variations of water sources in the Fayum, associated with (i) fluctuations in levels of Lake Qarun, (ii) Nile floods, and/or (iii) local runoff, hampers reliable interpretations on the interactions between prehistoric people and their local dynamic Fayum environment. Hence, the Fayum case study provides a unique

opportunity to test an end-member approach on sediment samples from the region, for enhancing insight into the morphodynamic development of the landscape in response to Holocene hydroclimatic variability.

The following research questions are addressed:

1. How can we identify main sedimentary processes in the Fayum Basin, from the combination of field observations and end-member modelling of GSDs?
2. Can we use such provenancing in the Fayum Basin to reconstruct environmental changes during wet and dry phases of the Holocene?
3. What is the relation between the modelling results and the Fayum Early to Middle Holocene (surface) archaeological evidence for occupation?

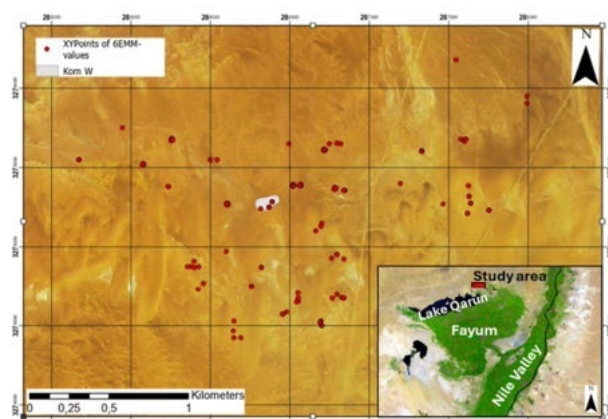


**Figure 1:** Detail of the western part of the study area, north of modern Lake Qarun, showing the location of sampled data-points across the present-day desert surface, used for spatial interpolation of the six end-members in the region surrounding Kom W (WorldView-2 imagery, 17 May 2012).

## Methods and Materials

We use an extensive dataset on sedimentology and geomorphology, retrieved from the Fayum region, north of present-day Lake Qarun (Fig. 1). Sediment samples ( $n=530$ ) were measured for grain size distribution with a laser-diffraction particle sizer (0.12-2000 microns). Statistical unmixing of GSDs into physically meaningful populations was performed with AnalySize v1.2.2 end-member modelling software. Spatial analysis of the EMM-output is

performed in a GIS-environment (ArcGIS). Published AMS radiocarbon age determinations on charcoal from hearths, embedded in different types of surface sedimentary facies, provide time constraints for the geomorphic reconstructions.

## Results

- Fitting statistics (sample and class-wise  $R^2$ ) indicate that a five end-member model would be sufficient to describe the Fayum grain size dataset. However, based on iterative processing between the modelling results and the lithofacies of known origin, a six end-member model suits the recorded sedimentary variation of the study area best. This referencing of the statistical end-member results, based on continuous iterations between field observations and process-based knowledge, leads to extra validation of the selected end-member model.

- The nine known sedimentary facies in the region are associated with four main depositional environments (i.e., lacustrine, ephemeral desert stream, deltaic, and aeolian). The nine facies are composed of (a combination of) the six identified end-members. The results indicate the reworking and winnowing of sediments of local provenance by wind and water action during both wet and dry phases in the region, as well as to an external source of water associated with the inflow of Nile waters into the Fayum depression.

- Interpolation of the spatial variation of the six end-members over a densely sampled part in the west of the study area, indicates the configuration of specific end-members across the present-day surface (or just beneath a thin layer of desert pavement). This enhances our understanding of the processes of erosion and deposition that shape today's desert land surfaces in the region surrounding Kom W.

- The six EMM-output also allows incorporation in vertical sedimentary sequences that potentially reflect lake high and low-stands, that can be related to past hydroclimatic changes.

- End-member variability across the present-day surface will be compared to the spread and content of the surface archaeological record (e.g., hearths and artefacts associated with types of sedimentary facies). This will lead to



new insights into the timing of landscape changes that shape the Fayum sedimentary record and affect the preservation, exposure and visibility of the (surface) archaeological record. Outcome may be used to infer if people in the past were targeting specific types of sedimentary facies.

#### Discussion and Conclusion

In our study we demonstrated that end-member modelling is a valuable tool for increasing knowledge of landscape development of complex sedimentary settings. The selected six end-member model, suitable to describe the sedimentary variability of the Fayum, can be applied to study the relation between the geomorphic reconstructions and the evidence for past human occupation. Based on the results, it is clear that this quantitative tool is especially important in the early phases of geoarchaeological research, as it initially provides a broad overview of the geomorphic setting of a study area, that can be used further to pinpoint specific parts of the landscape that may be suitable for in-depth examination. Geoarchaeologists involved in studies on past human-environment interactions can benefit from the applied end-member modelling approach, as it enhances palaeo-geographic and environmental reconstructions of complex sedimentary settings throughout the world.

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#### 162. Lower Palaeolithic hominin activity at the Lesvos wetland: a view from agent-based modelling and affordance analysis

*Simon Kübler (Ludwig Maximilian University of Munich)*

*Peny Tsakanikou (University of Crete)*

*Nena Galanidou (University of Crete)*

#### Introduction

"Mapping Hominin-Landscape Interactions in the Wetlands of Palaeolithic Lesvos: the Evidence from the Coastal Rims" (HomLandWet) project was a two-year project aiming to explore hominin-landscape interactions on and around the Quaternary wetlands of Lesvos Island in NE Aegean, through the investigation of the archaeology and palaeogeography of the present-day coastal rims and shallow sea waters. Archaeological evidence from Rodafnidia, a stratified open-air Acheulean site close to the SE Kalloni Gulf rim, combined with surface evidence from southern Lesvos, give a strong Lower Palaeolithic signal with minimum dates to the second half of the Middle Pleistocene (Galanidou 2023; Tsakanikou et al., 2021; Galanidou et al., 2016). Kalloni Gulf today is an extensive and shallow lagoon. Palaeogeographical and marine geophysical work suggest that during the glacial lowstands of the Pleistocene, the Kalloni Gulf and its coastal margins were transformed into fresh or brackish water wetlands or lagoons or mere plains, expanding the productive zone for hunter-gatherers to areas that today lay underwater. Against this dynamically changing landscape we set out to explore the methodological challenges in order to put flesh to this palaeogeographic scenario.

## Methods and materials

More specifically we wanted to investigate (a) the level of attractiveness of the affording environments (ecological properties), and (b) the dispersal possibilities conditioned by (palaeo)landscape structure and dynamics (palaeo-geographical implications). In terms of methodology, these issues cannot be explored but within an interdisciplinary framework. The study of edaphics, a proxy method from geosciences, was applied on- and, for the first time, off-shore, to test the working hypothesis that it was the eco-diversity of what are today coastal rims that attracted animal and hominin groups. Modern soils and rocks were chemically analysed to trace mineral nutrients that have long sustained plant, animal and human populations. These patterns served as indicators of potentially resource-rich zones in the past. The results provide the basis for testing three dispersal scenarios using agent-based modelling: (1) geoedaphic properties alone, (2) (palaeo)landscape structure alone and (3) a combined model integrating both.

## Results

Wetlands emerge as attractive hotspots over the palaeolandscape of Lesbos due to their variable ecological qualities. Kalloni wetland dominates over a wider resource-rich corridor within which occupation and dispersal would have been possible and viable, as reflected in the archaeological evidence and further supported by available affordances and topographic characteristics. Results suggest that behavioural parameters relevant to selection/avoidance of certain environments/habitats/areas are at play and should be taken into consideration in any attempt to model hominin subsistence and mobility patterns. A broader discussion is then enabled on suitability, connectivity and seasonal dynamics implicating hunter-gatherers' decision-making.

## Discussion

Proxy methods and modelling approaches inevitably involve issues of accuracy and resolution, especially for deep-time reconstructions. Nonetheless such frameworks are essential – not to re-create past conditions but to test new hypotheses and guide future research. The methodological approach applied to Palaeolithic Lesvos underscores wetlands as crucial settings for

human activity moving the interpretive focus beyond purely terrestrial or underwater contexts. It provides a transferable paradigm for investigating similar transitional environments between land and sea across and beyond the Aegean region.

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## 178. Rocky Roads: Simulating Neanderthal Mobility and Lithic Resource Use in the Liguro-Provençal Arc during MIS 3

*Amélie Vallerand (University of Montreal)*

*Claudine Gravel Miguel (New Mexico Consortium)*

*Julien Riel-Salvatore (University of Montreal)*

Understanding Neanderthal land-use and resource exploitation during Marine Isotopic Stage 3 (MIS 3 – 57-29ky BP) is central to discussions of their behavioural complexity and adaptability. Yet, the fragmentary nature of the archaeological record and the invisibility of behavioural processes make these questions difficult to address with traditional archaeological tools. This paper explores how integrating Geographic Information Systems (GIS) and agent-based modelling (ABM) can provide new insights into Neanderthal mobility patterns, raw-material acquisition, and landscape use in the Liguro-Provençal arc.

Our approach combines palaeoenvironmental reconstruction, spatial analysis, and computational simulation to model how topography, raw-material accessibility, and energy expenditure may have shaped Neanderthal mobility strategies. GIS serves both as a spatial framework and as a data integration platform, allowing the combination of terrain, hydrology, geological maps, and site distribution. Archaeological and geological data from key Middle Palaeolithic sites such as Riparo Bombrini and Arma Veirana inform the structure of the model, while environmental variables are derived from digital elevation models and slope analysis.

The agent-based model, implemented in NetLogo, simulates Neanderthal groups moving through a GIS-based virtual landscape. Agents engage in behaviours such as raw-material collection, tool production and discard, and site occupation while navigating environmental constraints represented in the GIS layers. Movement routines incorporate least-cost path (LCP) analysis derived from slope and terrain data, allowing the estimation of travel time

and energetic costs. Parameters such as group size, movement frequency, and raw-material abundance are informed by archaeological, ethnographic, and experimental data on hunter-gatherer behaviour. This allows us to propose a multi-scale approach to Neanderthal mobility, distinguishing between local, territorial, and regional levels of movement. The first model—focused on the local scale—seeks to quantify the relationships between occupation sites and raw-material sources, offering a dynamic framework to explore resource procurement strategies. Future versions will expand the spatial and temporal scope to evaluate broader settlement dynamics and environmental change across MIS 3.

Beyond the development of a specific model, this research addresses broader methodological questions relevant to Palaeo-GIS. It examines how computational simulations can help overcome the analytical challenges posed by sparse data, vast spatial scales, and the difficulty of inferring behaviour from material remains. The integration of GIS and ABM allows the explicit modelling of processes and interactions such as moving beyond static cartography towards generating dynamic hypotheses about human–environment relationships. This work also reflects offers new avenues to critically assess the epistemological limitations of such models, emphasizing that their value lies in exploring uncertainty and generating testable hypotheses rather than reproducing the past in detail.

Ultimately, this study aims to demonstrate that combining Palaeo-GIS with ABM offers a powerful experimental framework for reconstructing the mobility of Neanderthals and other Pleistocene populations. It highlights the potential of computational methods to make visible the hidden processes behind archaeological patterns and to link environmental affordances with human decision-making in deep time.

## 253. Geospatial predictive modelling of prehistoric rock shelter sites: A case study from eastern South Africa

*Felix Weinschenk (ROCEEH/University of Tuebingen)*

*Gunther Heinz Dietrich Möller (University of Tuebingen)*

*Lawrence Msimanga (ArcheoTask)*

*Volker Hochschild (University of Tuebingen)*

*Manuel Will (University of Tuebingen)*

*Christian Sommer (ROCEEH/University of Tuebingen)*

The archaeological record of the Middle Stone Age period in South Africa is exceptionally rich in terms of the number of sites, temporal resolution, and diversity of cultural traits. However, their spatial distribution is biased and clustered, especially in the Eastern Coastal Hinterland. We therefore present our methods and results for predicting potential rock shelter site locations in the surroundings of Jojosi, an extensively used open-air site in the South African province of KwaZulu-Natal (Will et al. 2024, Möller et al. 2025).

Site observations were collected from the literature (Mazel 1989) and an initial field campaign in 2024. We configured the mobile app KoboToolbox to collect and verify GPS coordinates, site characteristics (type, size, etc.) and archaeological relevance (sediment bodies, archaeological surface finds, disturbance, etc.). The resulting database, containing more than 30 rock shelter observations, was then used alongside environmental variables to train predictive models that identify locations with comparable characteristics.

Covariate selection has a major impact on prediction results and therefore requires thoughtful consideration. We developed a framework in which we (i) first observed a number of sites in the field, (ii) characterized the geomorphic factors and processes responsible for their formation (topography, lithology, hydrology, etc.), and (iii) developed dedicated GIS analyses to generate spatially continuous maps of these characteristics (e.g. meaningful lithological contacts, breaks in drainage lines, etc.). These were then (iv)

subjected to a series of statistical tests and filtering steps to avoid problems arising from correlation and collinearity among modeling covariates.

Finally, we trained and tuned three different machine learning models, predicted potential rock shelter suitability, and compared their results. We chose to compare Generalized Additive Models (GAMs) based on binomial logistic regression as a representative of classical statistical approaches, Maximum Entropy (MaxEnt) modeling for its capability to use presence-only data, and Random Forest because of its wide applicability and robustness. The results were compared in terms of spatial overlap, feature importance, and performance metrics. We furthermore address the effect of different spatial subsampling strategies on our study, which is characterized by a low number of observations—a situation typical for archaeological prospecting. We critically reflect on the needs and advantages of predictive modeling for field survey. Many of the sites observed and verified in the field follow geomorphic characteristics that can also be identified by consulting appropriate geological, geomorphological, and topographic maps in relatively little time and at low cost.

In contrast, computational methods can predict across vast spatial extents but require intensive preparation. If done correctly, they are reproducible and, depending on the model type, sometimes interpretable, but they remain affected by many individual choices made by the programmer.

Given the limitations of time and funding to actually visit the predicted sites, we raise the question of whether extended fieldwork combined with low-cost “pen and paper” approaches provides a better trade-off than costly computational methods.

Nevertheless, the process of building a geomorphologically informed predictive model helped us to formalize these characteristics in a quantifiable way, and thus to better understand site formation processes.

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## 258. The SUGAR ecosystem: Integrating archaeological data management and GIS-driven analysis for multi-layered Pleistocene excavations

*Xavier Roda Gilabert (Universitat Autònoma de Barcelona)*

*Susana Vega Bolívar (Universitat Autònoma de Barcelona)*

*Xavier Sánchez-Martínez (IPHES-CERCA, Universitat Rovira i Virgili)*

*Sofía Samper Carro (Australian National University)*

*Jorge Martínez-Moreno (Universitat Autònoma de Barcelona)*

*Rafael Mora Torcal (Universitat Autònoma de Barcelona)*

The study of human prehistory requires an integrative approach capable of linking environmental, cultural and behavioral data across vast spatial and temporal scales. Although Geographic Information Systems (GIS) are widely recognized as powerful tools for managing and analyzing complex datasets, their practical application in prehistoric research remains comparatively underdeveloped.

At the same time, the standardization of archaeological data management remains a key challenge for scientific research, long-term knowledge preservation, and interdisciplinary collaboration (Roda Gilabert & Mora, 2014). In response, the SUGAR ecosystem proposes a comprehensive framework for archaeological data integration and spatial analysis, designed to enhance interoperability, theoretical flexibility, and methodological transparency, particularly within multi-layered Pleistocene contexts.

SUGAR (Software Unified for Governance of Archaeological Management) is a technological solution designed to meet the methodological and analytical needs of Pleistocene archaeology. Initially created in 2004 (Mora et al., 2010), the software has been tested in field and laboratory research over a period of two decades. It is now publicly available at a high technological readiness level (TRL 8) and is suitable for academic and professional use. Its technical architecture is based on the Microsoft .NET Framework, and it is compatible with MySQL, PostgreSQL, and Microsoft Access databases. SUGAR also integrates components such as DevExpress, ensuring a scalable and sustainable platform, as well as inventorying with Data Matrix codes (Martínez-Moreno et al., 2011).

This paper has two aims: first, to present the conceptual and technical development of Q-SUGAR (QGIS Suite for Unified Geo-data in Archaeological Research); and second, to discuss how prehistoric GIS applications can evolve from data management to reflexive analytical frameworks (Mora et al., 2014; de la Torre et al., 2014).

Q-SUGAR is a free, open-source plugin that combines the GIS capabilities of QGIS with the archaeological data management system SUGAR. This creates a single workflow that covers everything from collecting field data to spatial analysis and long-term preservation. The plugin enables researchers to import, manage, analyze and visualize archaeological datasets directly within QGIS, supporting the integration of diverse spatial and contextual information. Key features include data integration and management via direct connections to relational databases such as MySQL and PostgreSQL/PostGIS, as well as CSV and SHP files, with synchronization to SUGAR tables. The plugin also offers spatial processing tools for generating vector layers,

automated stratigraphic sections and 3D visualizations via the QGIS 3D Map Viewer.

Q-SUGAR supports a wide range of GIS analytical methods, including spatial clustering, geostatistics and the reconstruction of material distribution or re-fitting networks. It also provides automated reporting and cross-platform interoperability, ensuring compatibility with used research software. The plugin is developed in Python and relies on the PyQGIS API and GDAL/OGR for spatial processing, with PostgreSQL/PostGIS serving as the primary storage system.

Beyond technical efficiency, Q-SUGAR enables a conceptual shift in archaeological GIS from descriptive cartography to dynamic interpretative analysis. Its capacity to integrate heterogeneous datasets (e.g. geology, artefact typology and site formation processes), supports multi-scalar interpretations of archaeological contexts and long-term human occupations. Thanks to its open design, data structures and analytical workflows can be adapted to research priorities rather than being constrained by fixed standards. This flexibility fosters the development of custom analytical tools, particularly valuable in Paleolithic research, where evidence tends to be fragmented and multi-layered.

The SUGAR ecosystem demonstrates how GIS and data infrastructures can evolve to meet the conceptual and practical demands of prehistoric research by linking field documentation, spatial analysis, and interpretive synthesis within a unified framework (Martínez-Moreno et al., 2016; Mora et al., 2020). Case studies from Paleolithic and later prehistoric sites show how SUGAR and Q-SUGAR can be utilized in tandem to facilitate in-depth empirical investigations, proving that GIS has the potential to be more than just a technological framework, and can be a critical instrument for understanding human behavior and material culture.

Keywords: software; data management; GIS; digital humanities; open science.

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### 349. Endless desert, endless possibility - Survey planning, data collection and data storage of the ARIMAS project

*Matthias Blessing (University of Vienna)*

*Aurore Val (CNRS)*

*Kaarina Efraim (National Museum of Windhoek)*

*Dominic Stratford (University of Witwatersrand)*

*Christian Sommer (University of Tübingen)*

The ARIMAS project is a large-scale survey and excavation project in southern Namibia initiated in 2021. Over the past 4 years, a prospection survey identified a plethora of previously unknown archaeological sites, among which several extensive open-air lithic scatters present the largest challenge in terms of survey planning and archaeological data collection. Studying these open-air scatters in an extreme environment, not only puts physical demands on the researchers themselves, but also requires careful preparation and efficient approaches to data collection and storage. We introduce our hardware setup for field surveys based on differential GPS, earth observation drones, and communication systems, which is capable of operating under adverse conditions such as limited power supply and the absence of mobile internet. Situated along ephemeral rivers, the scatters need to be contextualized with geomorphological data derived by a combination of remote sensing, ground measurements and sedimentological analyses, in order to critically evaluate preservation and post-depositional influences on spatial patterns. We therefore combine Visible, Near-Infrared, and Shortwave Infrared (VIS/NIR/SWIR) multispectral imagery to derive mineral indices and apply machine learning classification to create high-resolution lithological maps that form the foundation for geomorphological maps. Since some of the lithic scatters extend over several square kilometers, taking a spatial sample also requires careful planning. For an optimized analytical procedure, the various data strands need to be merged in a geospatial database that allows to combine a plethora of different formats and is accessible from

various locations at the same time. Our spatial data infrastructure (SDI), based on GeoNode, integrates PostGIS and GeoServer instances and enables the storage, access, and exchange of data via standardized protocols, as well as the visualization of results in desktop GIS software and browser-based data portals. The ARIMAS project aims to be a model project in terms of archaeological survey planning, data collection and storage in extreme and remote environments without modern infrastructure.

### 367. Predicting Palaeolithic Site Distribution Using MaxEnt Modelling in the Walannae Formation, South Sulawesi (Indonesia)

*Putra MUHAMMAD (National Museum of Natural history in Paris)*

*Akin Duli (Hasanuddin University)*

*Hasanuddin Hasanuddin (National Research and Innovation Agency of Indonesia)*

*Budianto Hakim (Pusat Kolaborasi Riset Arkeologi Sulawesi (Collaboration Research Centre of Archaeology))*

Sulawesi (Indonesia) lies within Wallacea, a biogeographical region that was never connected to the Asian mainland; therefore, it is critical for understanding hominid dispersal across island Southeast Asia. The earliest hominid presence in Sulawesi is documented on the Walannae formation, South Sulawesi, with recent evidence suggesting early occupation on the island around one million years ago (Hakim et al., 2025). Walannae Formation extends around 270 km north–south along the ancient and modern Walannae River and spans several regencies, including Soppeng, Bone, and Bulukumba. Despite this, archaeological research has concentrated on the northern parts of the formation. However, the southern parts, particularly Sinjai Regency, remain poorly explored despite their geological potential for site preservation.

Early Palaeolithic research in Sulawesi is challenged by the predominance of surface finds, limited stratigraphic, sedimentological, biostratigraphical data and widespread chronological data. This results in small and unevenly distributed presence-only datasets. These barriers make the application of spatial and predictive modelling approaches in tropical environments more complicated. This study applies Maximum Entropy (MaxEnt) modelling to predict the potential and distribution of early Palaeolithic site locations in the southern part of the Walannae Formation. Due to the condition of presence-only data and small training samples, MaxEnt was suitable for this research. A total of 41 early Palaeolithic site locations compiled from literature (published and unpublished), of which 25 were used as training data. Environmental proxies included elevation, aspect, slope, lithology, and proximity to modern river systems. Omission rates, Commission analyses, and variable contribution through the jackknife test were used to assess model performance.

Predictive model identified several high-probability zones, which were subsequently targeted for field survey. This approach led to the discovery of five new archaeological sites yielding 51 lithic artefacts. The assemblages are typologically comparable to those from the Cabbenge, Bone, and Herlang prehistoric areas and are consistently associated with ancient river terrace geomorphology, supporting the predictive validity of the model. This study demonstrates the effectiveness of MaxEnt-based predictive modelling as a tool for archaeological prospection and contributes to refining models of early human dispersal and technological variability in island Southeast Asia.

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### 387. Accounting for uncertainty in sea-level reconstructions using Bayesian hierarchical modelling: A case study from Mesolithic western Sweden

*Isak Roalkvam (Aarhus University)*

*Victor Lundström (Rio Göteborg)*

Changes to the position of the sea relative to land is integral to the reconstruction of paleo-environments and to the understanding of human use and traversal of coastal environments. Furthermore, recent developments in the statistical treatment of relative sea-level change through the use Bayesian hierarchical modelling is yet to be comprehensively incorporated in archaeological research. This framework allows for the integration of dimensions of uncertainty that are often overlooked in more traditional approaches to sea-level reconstructions. These have often treated indicator records for the past position of the shoreline as errorless in time and space, and subsequently drawn on these to establish time-series for sea-level change using either intuitively hand-drawn trajectories of sea-level change or by fitting simple polynomial models to this data. Bayesian hierarchical modelling, on the other hand, allows for the data-level uncertainty as related to spatial and temporal error associated with individual indicator records to be integrated with more flexible frameworks for modelling the trajectory of sea-level change, such as through non-parametric Gaussian process models (Ashe et al. 2018). This paper aims to demonstrate the benefits of adopting a Bayesian hierarchical

statistical modelling approach in the reconstruction of paleoshorelines, and will illustrate this with a case study of coastal settlement patterns from the Mesolithic of western Sweden.

#### Methods and materials

Geologically derived evidence for the past position of the shoreline in western Sweden has been gathered in the period from the late 1960s to the early 2000s (see Pålsson & Andersson 2005). This means that the available data is of a highly variable and generally lower quality when compared to data retrieved using more recent methods for sampling and chronometric dating. Furthermore, the indicative meaning of these records has often been taken to be that they represent sea-level index points (SLIPs). That is, estimates for points in time and space for the position of the shoreline, irrespective of the type of proxy in question. More recent and critical interpretations of the proxy records would instead often demand that these are seen as less informative marine or terrestrial limiting points (MLPs and TLPs). That is, instead of information on where the sea was, these are often more sensibly treated as indicators of points in time and space for where the sea was or was not present.

The available geological data is therefore hefted with considerable uncertainty both when it comes to their date, elevation and the indicative meaning of each individual proxy record, thus impacting the certainty with which the data can be drawn on to fix the position of the shoreline by altitude relative to the present sea-level over time. To properly account for these uncertainties, we first review the available original data from two chosen study areas of western Sweden, namely the regions of Strömstad and Göteborg. The data is classified according to their indicative meaning and ascribed chronological, elevational and inferential error associated with different proxy types using established protocols from the geological literature (e.g. Hijma et al. 2015). Furthermore, while archaeological evidence that can be linked to the position of the contemporary shoreline has sometimes been included in earlier geological reconstructions, this has only been done to a limited extent in

western Sweden. In addition to the geological data, secure archaeological radiocarbon dates are therefore also included in our modelling efforts. While the precise relationship between various archaeological phenomena and the sea can be difficult to establish, most of the archaeological remains can be securely interpreted as having been deposited on what would have been dry land, thus representing TLPs.

Having established these so-called data level models, a prior process model is then conditioned on the modelled data to provide the posterior estimate for relative sea-level change over time for each of the two case study areas. The prior model chosen here is a Gaussian process model, suitable for time-dependent and irregularly distributed data. With the estimates of the vertical change in sea-level over time, the topographical implications of the changing sea-level is then visualised by creating a series of maps for different time intervals with adjusted sea-levels that include the uncertainty in the estimates. By plotting the relative position of sites, this is used to illustrate the implications a more thorough modelling strategy can have for how we interpret settlement patterns relative to the contemporaneous sea-level when the uncertainty in the underlying data is more properly accounted for.

#### Results and further research

The results of the undertaken reconstruction efforts can be drawn on to interrogate a range of questions related to the distribution of archaeological remains relative to the sea, whether these are of a quantitative or qualitative nature. Furthermore, explicitly quantifying the uncertainty associated with a sparse data set of sea-level indicators of highly variable quality can be drawn on to plan targeted fieldwork to retrieve proxy records that improve parts of the shoreline displacement reconstructions that are especially uncertain, or target these towards periods that are of a special archaeological interest that demand a higher resolution. Finally, as an initial modelling effort, this study focuses on two constrained areas where the spatial variability induced by physical processes that cause irregularities in sea-level change in space can be assumed to have limited effect. Future work will expand on these initial

modelling efforts to explicitly model the spatial structure underlying the reconstructions.

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## 409. Settlement Development in the Okluky River Basin in the Light of Current Archaeological Evidence

*Klára Augustinová (Archaea Olomouc)*

*Tomáš Krampera (University of Hradec Králové)*

The purpose of the presentation is to outline the preliminary findings of the master's thesis entitled *Settlement Development in the Okluky River Basin in the Light of Current Archaeological Evidence*. The principal objective of the study is to provide a comprehensive analysis of the settlement patterns within a microregion of the southeastern Moravia, tracing the diachronic development of human occupation from the Palaeolithic through the Bronze Age. The deliberately delimited study area encompasses a territory that was continuously and intensively occupied throughout prehistory, protohistory, and the early medieval period. From a broader perspective, the examined

microregion can be characterised as a transitional zone—both geomorphologically and a culturally linking several developmentally distinct areas. Consequently, the region is not conceptualised as a closed analytical unit but rather as a dynamic landscape shaped by the interplay of natural and anthropogenic factors, as well as by its interaction with adjacent regions.

Southeastern Moravia constitute an extensive geographical zone whose distinctive environmental conditions have long provided a favourable setting for cultural and historical development throughout prehistory, early history, and the early medieval period. In order to capture the dynamics of settlement development within the selected territory, the thesis adopts a chronological framework extending from the Palaeolithic to the Bronze Age. The research pursues several primary objectives: based on available formal and spatial archaeological data, it seeks to reconstruct the long-term trajectory of human settlement within the study area and to evaluate selected aspects of past human societies in light of the current state of archaeological research.

To achieve a more comprehensive understanding of the southeastern Moravia region as a whole, the study also engages comparative analysis with other, more or less distinct, settlement regions and examines past interactions between human communities and their natural environment.

Within the geographically defined Okluky River basin, the thesis investigates settlement and socio-economic structures serving as key indicators of anthropogenic activity, the surrounding landscape character, and material culture, examined in their diachronic context. Wherever possible, the study compiles archaeologically exploitable data from a wide range of sources.

From a methodological standpoint, the research is based on a synthesis and critical interpretation of existing archaeological evidence derived from rescue excavations, supplemented by unpublished observations and fieldwork conducted by local amateur archaeologists active within the microregion. In the methodological framework of the thesis, predictive modelling techniques implemented within the ArcGIS environment will be employed. Based on a set of predefined parameters – such as slope orientation (aspect), elevation, gradient, proximity to watercourses, and related topographic

variables – the analysis aims to verify previously known archaeological sites and to predict potential new sites of past human activity. The reliability of the predictive models will be verified against already known archaeological sites. This verification process will enhance the overall credibility and predictive accuracy of the model with respect to potential new sites of past human activity. The final version of the thesis will incorporate a comprehensive database of both previously recorded and newly identified sites, compiled from excavation reports and other relevant documentation.

Based on the available formal and spatial datasets, the thesis aims to address the following research questions:

1. What specific changes can be observed in the dynamics of settlement development across successive archaeological periods within the study area?
2. Can settlement continuity be demonstrated between chronologically successive cultural entities within the given microregion, or does the evidence suggest discontinuity?
3. How do the relationships between archaeological components and individual parameters of environmental analysis vary? Are consistent patterns observable according to component type?
4. Are there significant differences in settlement strategies within the studied region across the defined chronological sequence and in comparison, with other regions of southeastern Moravia? If so, what environmental or cultural factors may have conditioned these differences?

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Acta musealia. Museum jihovýchodní Moravy ve Zlíně p.o., roč. 15, 1-2, s. 8–27. ISSN 0862-8548.

## 442. Ecological Gradients as Sandboxes: Complexity, Environment, and Social Hierarchy

Chiara Girotto (LMU)

This paper explores how ecological gradients can serve as conceptual “sandboxes” for modeling the emergence of social complexity in prehistory. Social change is most often explored by means of artefacts or site distributions – material culture and settlement patterns as reflection of horizontal and vertical hierarchies. Especially in prehistory, the meaning of the objects or sites – the tip of the iceberg of behavioural patterns, these symbols of socio-cosmological structures are often poorly understood.

Archaeology represents the *Longue Durée* of social change and further, humanity has been characterised by physicists as a prime example of a complex system. Generally driven by constant change – entropy vs. equilibrium, interaction is the key driving factor.

Stable environments may foster surplus and stratification, while unstable ones may produce scarcity and, paradoxically, similar hierarchical outcomes. By abstracting from specific datasets, this theoretical approach rethinks how environmental affordances—fertile plains, river systems, or marginal uplands—configure opportunities for social organization and cultural change. Rather than deterministic laws, such dynamics arise from non-linear behaviours inherent to the complex adaptive system of humanity. These behaviours are inherently tied to entropy and the second law of thermodynamics – entropy (‘statistical disorder’) in an isolated system can usually only increase but never decrease. Open systems allow for a decrease of local entropy but compensate by increasing the entropy of their surroundings. The passing of time is an essential component of change and the ‘arrow of time’ is a one-way direction. A cause will always precede the effect, time is

asymmetrical. This concept of irreversibility is not only tied to evolution but also to time perception and the formation of memory.

This is reflected in our past, highlighting humanities ability to be constantly adapting at the edge of chaos. The clock can never be “turned back”, it is not only impossible to recreate the starting point but randomness and interactions will always result in different outcomes. Innovation, flexibility, creativity and anti-fragility occur as an interactive feedback of co-evolution and self-organising criticality - especially in decentralised, low hierarchy environments fragility (e.g. Strogatz 1994)

Echoing Prigogine’s notion of dissipative structures (Prigogine 1945) and irreversibility, the necessity of the arrow of time and the idea that space in these systems can be both, physical and conceptual (Axelrod and Cohen 1999) we propose to interrogate how theoretical models, when mapped onto gradients, generate narratives about hierarchy and transformation. These ‘sandboxes’ aka the ecological gradients can be generated from available sources, e.g. merging bioclimatic variables from ‘PaleoClim’ with soil databases, terrain models, and hydrological. Weighting these factors in accordance with archaeological assumptions about the people’s ecosystem requirements allows the creation of differing ecological affordance maps with the use of R.

In doing so, the paper situates archaeological interpretation within broader debates in physics, philosophy, and complexity science, asking how we might critically model the fragile balance of adaptation at the edge of chaos.

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## 443. Challenges and Lessons in Palaeo-GIS: Modelling Late Neolithic Movement in the Mountain Landscapes of the Eastern Rim of the Tibetan Plateau

*Yidan Zhang (University of Oxford)*

In prehistoric mountain landscapes, GIS-based movement modelling offers unprecedented analytical reach—yet it equally exposes the fragility of our assumptions about terrain, hydrology, and climate. This paper presents a Late Neolithic movement-modelling case study from the eastern rim of the Tibetan Plateau, based on ten well-documented sites in northwestern Sichuan and southern Gansu. We ask why models succeed—or fail—in high-relief settings. We examine how river extraction and seasonal persistence, river-crossing rules, and the choice between aspect and modelled insolation shape least-cost corridors and inter-site connectivity. We also integrate palaeoclimate information, using third-millennium BC temperature and precipitation simulations, to test how wetter/warmer versus drier/cooler scenarios can reshape corridor geometry and route choice.

## Methods and materials

We implemented a stepwise palaeo-GIS workflow that links terrain modelling, climate-informed hydrology, and movement-cost integration. We used SRTM v4.1 (3 arc-seconds, ~90 m) as the primary DEM and selectively cross-checked key outputs with ALOS AW3D30 to balance accuracy and tractability across a large mountainous extent. Distance calculations were performed in the Asia North Equidistant Conic projection, and site coordinates were georeferenced from excavation maps and textual records.



Guided by third-millennium palaeoclimate scenarios, we extracted river networks from the DEM using a flow-accumulation threshold (baseline FAT  $\approx 5,000$ ) to suppress minor/seasonal tributaries and approximate a perennial network under third-millennium BC conditions; this palaeoclimate framing also informed river-buffer weighting (distance-to-water effects) and assumptions about hydrological persistence. We then combined six cost factors via the Analytic Hierarchy Process (AHP; CR  $\approx 0.0787$ )—distance to rivers, slope, vegetation, elevation, aspect/insolation, and land curvature—and transformed the AHP-weighted surface into an exponential affordance index (I), from which least-cost paths (LCPs) and connectivity outputs were derived.

To represent light–heat conditions in complex relief, solar radiation was modelled as direct insolation at winter-solstice noon and contrasted with aspect-only classifications; selection between aspect and modelled insolation was made per study area according to which better captured local conditions. In parallel, to make sensitivity and failure modes explicit, we compared two river-crossing rule sets throughout: rivers treated as uncrossable barriers versus graded crossing costs implemented through buffers.

Figure

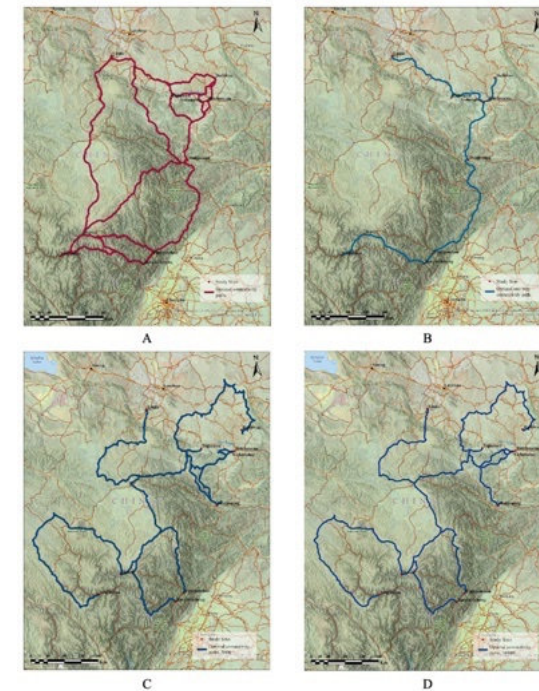


Figure Least-cost movement routes

We include a four-panel illustration. Panels A–B show two connectivity outputs derived from the same cost surface: A presents best inter-site connectivity paths, while B shows an end-to-end connectivity spine across the study extent. Panels C–D show the erroneous route geometries produced when rivers extracted at the stated FAT are treated as uncrossable barriers (C: FAT  $\approx 5,000$ ; D: FAT  $\approx 10,000$ ). Together, these panels show how hydrological parameterisation and barrier rules differentially affect local inter-site links and landscape-scale connectivity.

## Results

Hydrology rules dominate failure modes. Treating extracted rivers as absolute, uncrossable barriers produces implausible detours (several-fold

lengthening to avoid trunk valleys). Graded river-crossing costs, in contrast, yield valley-hugging corridors that are more consistent with landmark-guided wayfinding and provisioning needs.

Palaeoclimate coupling reveals sensitivity in corridor geometry. Scenario tests show that corridor outcomes are sensitive to palaeoclimate-informed assumptions about hydrological persistence and river-cost parameterisation. Given third-millennium BC fluctuations and an overall decline in temperature and precipitation, surface runoff likely changed and seasonal channels became more variable. In some sectors, ridge/pass options may therefore become relatively more competitive.

Factor contributions are strongly skewed toward water and slope. The AHP-weighted ranking is hydrology > slope > vegetation > elevation > aspect/insolation > curvature: proximity to water and slope largely determine corridor selection, while aspect/insolation mainly refines local plausibility rather than shifting regional corridors.

Aspect versus modelled insolation is context-dependent. In high-relief terrain, aspect alone can misrepresent local light–heat conditions; explicitly modelled insolation reduces classification noise in our case study, but the better choice should be assessed per study area by evaluating both metrics.

#### Discussion

A credible palaeo-GIS workflow for high-relief terrain hinges on four commitments, but it is strengthened when these methodological choices are tied back to interpretable corridor patterns.

First, our modelling identifies a set of low-cost corridors indicating that long-distance interaction across the eastern Tibetan Plateau margin is possible and comparatively economical under certain terrain–hydrology configurations. These corridors are not a single straight “highway” but an interlaced corridor ensemble that tends to follow intermontane basins and valley

systems while avoiding steep and high-elevation terrain. In our case study, low-cost bands concentrate within broadly favourable envelopes (e.g., moderate elevations, gentler slopes, and proximity to more persistent channels), forming elongated strips of higher affordance rather than discrete point-to-point lines. Importantly, high-cost zones—such as some high passes and divides—are not necessarily impossible to traverse, but would likely require stronger motivations (e.g., access to critical resources or seasonal mobility strategies) than routine inter-site movement.

Second, the workflow remains robust only if hydrology is treated realistically. River networks should be calibrated in light of third-millennium climate assumptions about runoff and channel persistence, and river-crossing should be modelled as graded costs rather than binary barriers; our documented “error modes” show that absolute-barrier rules can generate counter-intuitive detours.

Third, representing micro-environmental constraints requires a context-dependent choice between aspect and modelled insolation, evaluated per study area according to which better reflects local light–heat conditions in complex relief.

Fourth, DEM resolution and projection are not clerical background: they are reportable, testable parameters that shape reproducibility and should be explicitly documented alongside negative runs (e.g., barrier-style river settings).

Finally, least-cost outputs should be treated as hypotheses, not literal reconstructions. Factors difficult to quantify at corridor scale—visibility, weather, group size, transport mode, and social regulation of movement—may locally outweigh terrain-based optima. To strengthen interpretive credibility, we compare modelled high-affordance corridors with archaeological site distributions, including sites not used to build the model. In practice, most sites—including those not used as model inputs—fall within the modelled high-

affordance corridors or their buffers, providing independent, spatially consistent support for the plausibility of the inferred corridor ensemble and helping prioritise targets for further validation.

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## S40: Digital Archaeology for Heritage under Threat: Modelling Climate Hazards and Landscape Change

*Emeri Farinetti, Landscape Archaeology – Archaeological Theory and Methods, RomaTre University – Dipartimento di Studi Umanistici*

*Miltiadis Polidorou, Lab of Digital Humanities and GeoInformatics, Archaeological Research Unit (ARU), University of Cyprus*

*Fernando Moreno Navarro, RomaTre University – Dipartimento di Studi Umanistici*

*George P. Pavlidis, ILSP – Institute for Language and Speech Processing, ATHENA – Research and Innovation Centre in Information, Communication and Knowledge Technologies*

**Location:** Hörsaal 03

**Session Format:** Standard

Archaeological landscapes are shaped by the interplay between human activity and natural forces such as erosion, sedimentation, tectonic shifts, and climate-driven changes. Today, these same forces—accelerated by climate change—pose unprecedented risks to cultural heritage, from flooding and coastal erosion to extreme weather events and desertification. These dynamics not only threaten the material integrity of archaeological sites but also challenge how we document, interpret, and preserve the past for the future.

This session explores how digital tools and spatial geotechnologies can help monitor, model, and mitigate climate-related hazards in archaeological landscapes, while also enhancing our understanding of their long-term evolution. We welcome contributions that showcase innovative workflows, risk-assessment strategies, and predictive models at the intersection of geomorphology, archaeology, and heritage conservation.

Topics may include, but are not limited to:

- High-resolution digital terrain analysis for vulnerability assessment
- Remote sensing and change detection for hazard monitoring (e.g., LiDAR, photogrammetry, UAV surveys, geophysical prospection)
- Geoarchaeological case studies addressing climate-induced landscape transformations
- Simulation and predictive modeling of hazard scenarios and human–environment interactions
- Integration of hazard datasets into archaeological GIS and decision-support tools
- Digital Twins for real-time monitoring and adaptive heritage management
- GIS-based spatial modelling for cultural heritage risk mapping and resilience planning

We particularly encourage interdisciplinary approaches combining earth sciences, climate studies, and digital archaeology to develop proactive solutions for cultural heritage under threat. This session also aims to foreground the role of computational and spatial methods in climate change adaptation strategies, ensuring that archaeological data informs policy and resilience planning.

Join us to advance the discussion on how digital archaeology can be a key player in safeguarding cultural heritage from climate change, bridging the gap between research, technology, and heritage protection.

**08:30 – 08:50** 82. Orbit-to-Action: A Three-Tier Data Driven Framework for Climate-Resilient Cultural Heritage Response  
*Pouria Marzban\**; *Elvira Iacono\**; *Bernhard Fritsch\**; *Benjamin Dücke\**

*\*DAI*

**08:50 – 09:10** 149. SAR for Heritage Protection: Detection of Small-Scale Looting Holes

*Cem Boyoglu (Wuhan University); Timo Balz (Wuhan University)*

**09:10 – 09:30** 180. Texturing Computed Tomography 3D Models using Multimodal 3D Reconstruction  
*Stephan Costopoulos (Athens University of Economics and Business); Georgios Papaioannou (Athens University of Economics and Business)*

**09:30 – 09:50** 225. Developing a Coastal Change Vulnerability Index for Archaeological Sites along the Lebanese Coast  
*Celia Prescott (University of Southampton)*

**09:50 – 10:10** 269. Modelling soil loss and deposition in Monti Lucretili (Italy): a multi-temporal approach  
*Giordano De Coste (Università degli Studi Roma Tre)*

**10:10 – 10:30** 293. Integrating Optical and Radar Remote Sensing to Monitor Urban Sprawl and Assess its Impact on the Ancient Egyptian Cultural Heritage at Bawiti, Bahariya Oasis  
*Mina Yacoub (LMU Munich); Nicola Lercari (LMU Munich)*

**10:30 – 11:00** Coffee break

**11:00 – 11:20** 304. Annual-scale soil erosion monitoring using high-resolution UAV-collected DEMs at the Medieval Silk Road settlement of Ak-Beshim, Kyrgyzstan  
*Patrick Cuthbertson (Central Asian Archaeological Landscapes Project (CAAL), UCL; Centre for the Archaeology of Human Origins (CAHO), University of Southampton); Gai Jorayev (University College*

*London (UCL), Macao University of Tourism); Marco Nebbia (University College London (UCL)*

**11:20 – 11:40** 339. Unmanned Aerial Vehicle (UAV) Photogrammetry for Archaeological Documentation: A Case Study of Shahr-i Zohak, Afghanistan  
*Masood Zaman (Qayoom Ihsan Limited)*

**11:40 – 12:00** 439. Satellite-based Monitoring of Urban and Environmental Threats to the Lebanese Cultural Heritage: A Decade of Change at the Bronze-Age Site of Tell Fadous-Kfarabida  
*Georgios Leventis (ERATOSTHENES Centre of Excellence); Mahmoud Mardini (ERATOSTHENES Centre of Excellence); Hermann Genz (American University of Beirut)*

## 82. Orbit-to-Action: A Three-Tier Data Driven Framework for Climate-Resilient Cultural Heritage Response

*Pouria Marzban (DAI)*

*Elvira Iacono (DAI)*

*Bernhard Fritsch (DAI)*

*Benjamin Ducke (DAI)*

Archaeological and Cultural Heritage (ACH) sites face escalating risks from long-term climate change, extreme weather, and anthropogenic land-use pressures. To address these threats, the German Archaeological Institute (DAI) and partners established the Cultural Heritage Response Unit (CHRU). This contribution outlines the CHRU remote sensing and monitoring

framework, which delivers cost-effective, rapid decision support for damage assessment and on-site planning using multi-source satellite data and GIS. We structure our methodology into three coordinated components: (1) Preventive measures that integrate hazard and exposure modeling to prioritize at-risk ACH assets; (2) Time-series analysis and monitoring to detect gradual change and precondition signals (e.g., subsidence, hydrological risks, etc.); and (3) Rapid response workflows to map impact extents, quantify damage, and guide field deployment in the first hours to days after an event. The framework leverages open data from the EU Copernicus programme alongside partner-provided and subscription datasets to balance coverage, latency, and spatial detail.

Central to our approach is KGR Finder, an in-house toolbox that automatically maps ACH sites within defined risk footprints, simplifying prioritization, tasking, and reporting. We present recent case studies demonstrating how combined multi-source data stacks, reproducible processing chains, and interoperable GIS products translate satellite observations into actionable products for heritage managers. By coupling preventive analytics, continuous monitoring, and rapid mapping within our operational pipeline, the CHRU enhances climate resilience and supports the effective preservation of ACH sites globally. Furthermore, we provide an overview of the digital documentation approaches for safeguarding cultural heritage assets on the ground.

## 149. SAR for Heritage Protection: Detection of Small-Scale Looting Holes

*Cem Boyoglu (Wuhan University)*

*Timo Balz (Wuhan University)*

The looting of archaeological sites causes irreversible destruction of cultural heritage and scientific information. While remote sensing offers a monitoring solution, detecting small-scale looting holes ( $\leq 3\text{m}$ ) remains a significant



challenge. This study investigates the detectability of small-scale looting holes using high-resolution TerraSAR-X satellite imagery, combined with controlled field experiments and SAR simulation. After assessing looting holes in real archaeological fields from Turkey and Peru, we established an empirical detection threshold by creating our artificial looting holes, finding that holes  $\geq 2$  were consistently detectable, whereas a  $1 \times 1$  m hole was rarely visible. We supported our experiment with 3 different test, specially with one that overlooked by previous studies. SAR simulations successfully replicated real-world scattering phenomena, validating the approach for scenario testing. The research confirms the technical feasibility of using SAR for sub-3m looting hole detection, provides crucial guidelines for parameter selection, and identifies the path forward for developing automated monitoring systems, which is currently limited by a lack of labeled training data.

## Introduction

The true cost of looting is the destruction of cultural memory itself. Because archaeological sites are non-renewable, the unauthorized removal of artifacts severs their connection to history, causing an irreparable loss of scientific information (Proulx, 2013). While remote sensing offers a solution, its application to looting detection has been limited, especially for small-scale features ( $\leq 3$ m) which represent the majority of global incidents. The integration of very high-resolution (VHR) optical and SAR data marked a significant advance, as texture analysis allowed for the recognition of subtle looting signs even in challenging conditions (Tapete and Cigna, 2021). This study addresses this critical gap by investigating the detectability of small-scale looting holes using high-resolution TerraSAR-X imagery, controlled field experiments, and SAR simulation. Our research questions are: 1) What are the minimum detectable dimensions for looting holes using TerraSAR-X? 2) How do environmental factors and acquisition parameters influence detection? 3) Can SAR simulation effectively model these features to support future automated monitoring?

## Material&Method

Our methodology employed a three-pronged approach. First, we conducted investigations at archaeological sites in Zeugma (Turkey) and Nasca (Peru) using new and archive TerraSAR-X imagery to examine looting signatures under real-world conditions. Second, we executed a controlled field experiment in a field. We excavated two artificial looting holes: Hole 1 ( $1 \times 1$  m) remained static, while Hole 2 was systematically modified from  $2 \times 1$  m to  $2 \times 2$  m and finally to  $3 \times 1.2$  m (Fig. 1). We acquired 16 TerraSAR-X images in Starving Spotlight (ST) and High-resolution Spotlight (HS) modes, with varying orbits (ascending/descending) and polarizations (HH/HV), to monitor these features. We also conducted three targeted sub-experiments on Hole 2 to test the effects of water accumulation, camouflage coverage, and soil waste placement. Third, to improve the interpretation of SAR-derived features, we employed RaySAR (Auer et. al. 2016) to simulate looting hole scenarios under multiple incidence angles and look directions. We created 3D models of the looting holes and simulated their radar response under various conditions, including different incidence angles, vegetation obstructions, and water levels, to validate and extend our empirical findings.

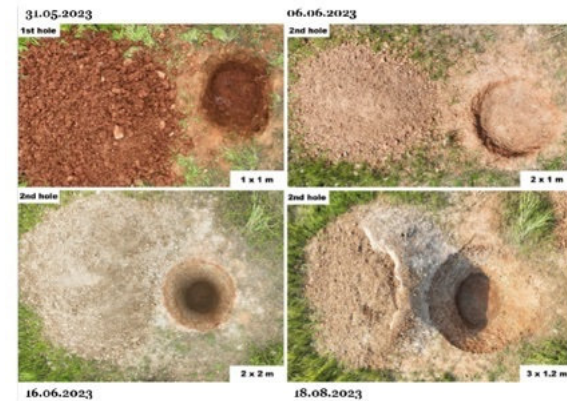


**Figure 1:** Artificial looting holes in different sizes



## Results

Our key results establish practical benchmarks for small-scale looting detection. From the controlled experiment, we determined a detection threshold: the 1×1 m hole was visible in only 1 out of 16 acquisitions, while holes  $\geq 2 \times 1.6$  m were consistently detectable. Optimal detection occurred with descending orbit, HH polarization, and  $\sim 29^\circ$  incidence angle. The sub-experiments revealed critical insights, water-filled holes became invisible due to signal reflection; camouflage coverage did not prevent detection; and, most significantly, the placement of soil waste (Fig. 2.) relative to the satellite's look direction had a decisive impact on detectability, a previously overlooked factor. In archaeological cases, Zeugma imagery clearly differentiated the geometric backscatter signature of subsurface holes from above-ground objects like trees. Finally, SAR simulations successfully replicated the geometric effects observed in real data, confirming the obscuring effects of vegetation shadows and water accumulation, and demonstrating the tool's utility for testing complex scenarios virtually.



Figure 2: Location of the soil waste (3D model)

## Discussion

This study provides the first empirical evidence that detecting sub-3m looting holes with SAR is technically feasible but operationally challenging. The identified detection threshold ( $\geq 2 \times 1.6$  m) and the critical influence of soil waste placement are vital considerations for designing effective monitoring campaigns. The ineffectiveness of camouflage is a significant finding for heritage security, while the invisibility of water-filled holes highlights a key environmental limitation. Our use of SAR simulation proved to be a powerful method for understanding scattering mechanisms and testing variables impractical

to replicate in the field. The high false-positive rate observed in coherence change detection underscores that fully automated monitoring remains a future goal, currently hindered by the lack of a dedicated, labeled dataset of looting features. The research underscores that technological solutions must be integrated with an understanding of site-specific environmental and anthropogenic factors. Our findings offer clear guidelines for parameter selection in heritage monitoring and define the necessary next steps toward developing automated detection systems.

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## 180. Texturing Computed Tomography 3D Models using Multimodal 3D Reconstruction

*Stephan Costopoulos (Athens University of Economics and Business)*

*Georgios Papaioannou (Athens University of Economics and Business)*

## Problem Statement

Computed Tomography (CT) has been widely applied to archaeological and biogenic materials to produce accurate representations of external and internal structure, features otherwise inaccessible through conventional

observation or invasive methods. CT has also been used when the materials are too reflective or transparent to allow surface-based methods to recover the shape, like structure from motion photogrammetry or laser-based scanning. Furthermore, micro-computed tomography (micro-CT) has allowed the accurate capture of very small and particularly thin structures, something nearly impossible with other techniques.

CT reconstructions, however, lack the optical properties that define the visual appearance of a surface. Conversely, image-based methods that synthesize three-dimensional geometry from optical data, such as Structure from Motion (SfM) photogrammetry, can effectively capture color variations in surface texture. Although tone mapping of the density transitions recorded by CT can produce a pseudo-coloring of the various density levels, this information alone is not sufficient for the color reproduction of the original, since materials with radically different reflectance and visible spectrum absorption characteristics very often have the same density in terms of X-ray absorption. In this study, we integrate two radically different surface reconstruction techniques, in order to transfer surface albedo from a less accurate yet textured photogrammetric reconstruction of an object onto a CT-derived isosurface mesh, which is bereft of any textural information. The proposed hybrid approach seeks to combine the geometric fidelity and volumetric accuracy of CT imaging with the high-resolution surface texture, obtained through photogrammetry, thereby improving both the visual and structural representability of reconstructed models, in line with recent advances in cross-modal registration between CT volumes and 3D point clouds (Saiti and Theoharis, 2022).

### Methodology and Materials

Building on earlier multimodal integration efforts combining photogrammetry and computed tomography for complete 3D digitization (Zhan et al., 2021), the proposed workflow integrates volumetric and image-based reconstruction techniques to facilitate the transfer of recorded average from an image-based approach like SfM to CT isosurfaces.

To diversify our experiments, we used two substantially different specimens. The first was a block of sediment full of bone fragments and other deposits, immersed in resin to strengthen its integrity prior to physically slicing and scanning it. Due to the resin impregnation, the surface exhibited strong reflectivity and glossiness. The second was a very thin and semi-translucent operculum fish bone. For both cases, the CT-derived density was uninformative for the coloring and characterization of the surface, and the image-based approaches to model the surface could not produce a faithfully reconstructed surface.

The input of the pipeline was the isosurface reconstructed from micro-CT data, and a photogrammetric model derived from image-based modelling. Micro-CT was initially used to nondestructively document the structural geometry and shape of the artefact. The output of the X-ray scan processing was a stack of volume slice images, from which a three-dimensional isosurface was produced, using a custom surfacing solution that could handle very large datasets (<https://github.com/cgaueb/surfacer>). To complement the volumetric dataset, an image-based reconstruction was generated via SfM photogrammetry, using Agisoft Metashape. The resulting model provided the color information for the color transfer. It is important to note that the photogrammetric model need not be very accurate, nor does it need to be a watertight, complete mesh, as long as it provides adequate coverage of the volume's isosurface after alignment.

The isosurface 3D model was further processed in Meshlab to remove all internal structures and retain only the outer shell of the object, which is mutually present in both modalities, resulting in significant geometry and processing time savings.

The first step of the workflow involves the geometric alignment of the two meshes. This is in general a semi-automatic process, involving a rough manual alignment and an automatic registration using a variant of the Iterative Closest Point (ICP) algorithm. Keep in mind that for cases where the photogrammetric model introduces minor distortions, a perfect alignment is impossible, without first applying manual de-warping or a non-rigid registration algorithm. Depending on the specimen, we have used Meshlab and Autodesk

3D Studio Max for automatic registration and manual alignment/de-warping, respectively.

Due to the dense isosurface, which can easily correspond to hundreds of millions of vertices, the volume isosurface was first decimated up to a controlled deviation and the mesh was parameterized using 3D Studio Max, although other tools could have been employed equally well.

The final stage is the texture transfer itself. Two established approaches may be employed in this phase. The first relies on direct texture “baking” by casting rays from the target mesh’s positions expressed in the texture parametric domain. The second involves sampling the closest mesh locations of the (textured SfM) source mesh from the vertices of the isosurface and then filling in the target texture with the interpolated data. The first approach is more meaningful when the source mesh constitutes a watertight surface itself, which can form an intersection hull for the rays that sample the textured surface. We successfully employed it for the texture transfer on the sediment block. The second approach is preferable when the textured surface is warped and/or partial. This was the case with the fish bone, whose SfM reconstruction resulted in a slightly warped mesh compared to the isosurface, with the thin edges of the bone being poorly defined.

## Evaluation and Results

As indicated in Figure 1, despite the intrinsic geometric discrepancies, evident in the geometric deviation visualization insets, the texture transfer was successful, enabling the generation of a geometrically precise textured output, by combining two modalities that excel only in one of the two aspects. The perceptual difference column was produced by rendering the SfM and textured isosurface after disabling shading, so that texture comparison is not biased by the different structural and relief details. For the perceptual difference measurement, the now standard FLIP method was used (Andersson et al., 2020).

The presence of the resin surface on the SfM model of the sediment block created an additional solid interface which was captured by photogrammetry. On the other hand, the volume segmentation and isosurface extraction

bypassed this more permeable layer and directly reconstructed the sediment itself, resulting in visible differences at the edges of the compared textured models. This is expected however. On the rest of the surface, only subtle differences are present, indicating a very successful texture transfer.

The situation was similar with the operculum bone, where noticeable image deviations were present only at the edges. Again, these differences were primarily due to geometric distortions of the SfM model, not the texture.

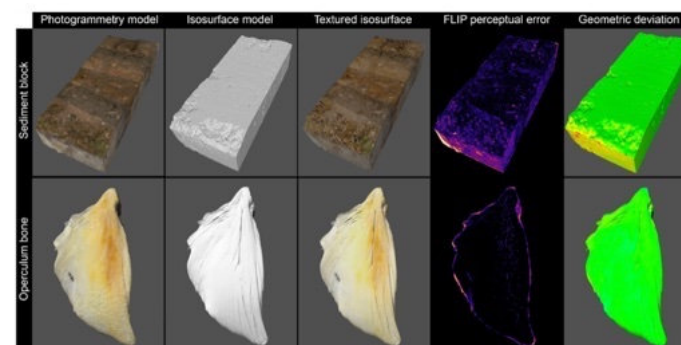


**Figure 1.** Comparative visualization of the two case studies: a resin-impregnated sediment block (top row) and a semi-translucent operculum specimen (bottom row). From left to right: photogrammetric reconstruction, CT-derived isosurface, detail-transferred model, FLIP perceptual error map, and geometric deviation map illustrating cross-modal correspondence.

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## 225. Developing a Coastal Change Vulnerability Index for Archaeological Sites along the Lebanese Coast

*Celia Prescott (University of Southampton)*

Climate change poses a clear threat to coastal cultural heritage through long-term sea-level rise, coastal erosion, and potentially more frequent flood events. These hazards are particularly important in Lebanon, where at least twenty-six archaeological sites and hundreds of features attest to millennia of near-continuous human settlement along a relatively narrow coast. Despite its rich material record, no national-scale assessment of coastal change hazards to heritage in Lebanon has yet been undertaken. Information on both coastal heritage and geomorphology is scattered across multiple sources and formats, and inconsistencies in data resolution make broad-scale hazard assessment difficult to approach.

This paper presents results from the development of a coastal change vulnerability index for archaeological sites along the Lebanese coast. The study compiles a national geospatial database of archaeological features that integrates archaeological and geomorphological attributes. Features within the database are co-registered, in GIS, with coastal erosion and flood hazard and assessed using open-source data on historic shoreline change rates and global sea levels respectively. The compiled information is used as a foundation to develop a vulnerability index which calculates a relative vulnerability score for each record as a function of variables relating to the exposure, sensitivity, and adaptive capacity of archaeological features to coastal change hazard. Variables are chosen, scaled and weighted according to previous

workflows and tailored to Lebanon’s specific archaeological and environmental context.

By enabling the vulnerability of individual features to be ranked and visualised spatially, the research provides an effective tool for both heritage management and climate change policy development. The resulting database also provides the baseline for further research into the impacts of coastal change on tangible cultural heritage in Lebanon.

## 269. Modelling soil loss and deposition in Monti Lucretili (Italy): a multi-temporal approach

*Giordano De Coste (Università degli Studi Roma Tre)*

As is well known, land use underwent profound transformations throughout the last century across the Italian Peninsula. Coastal regions generally experienced an intensification and mechanization of agricultural practices, together with the expansion of areas devoted to monocultures. At the same time, climatic conditions have also changed, and today we are witnessing increasingly dramatic events ranging from prolonged droughts—especially during the summer months—to sudden and intense rainfall. Both these anthropogenically driven environmental factors have significantly influenced the intensity of geomorphic processes such as erosion and sedimentation, which in turn affect the preservation and visibility of cultural heritage and the archaeological landscape.

However, the situation is somewhat different in mountain areas. While it is undeniable that climate change equally affects both lowlands and uplands, land-use patterns have followed a different trajectory in the latter environments. Here, villages became partially depopulated, and agro-pastoral practices were often abandoned, allowing for woodland regeneration over the past seventy years. On one hand, this process mitigates soil degradation and its impact on both buried and surface archaeology; on the other, it marks the disappearance of traditional management and exploitation practices—as

well as the knowledge that sustained them—which were essential to the survival of mountain communities until only a few decades ago.

This is also the case of Monti Lucretili, a mountainous district in the central Apennines located roughly 60 km northeast of Rome, which constitutes the focus of this contribution. By leveraging historical cadastral maps and aerial photographs, the evolution of land use over the last two centuries is outlined. Moreover, in combination with pluviometric data recorded since the early 20th century—which also reflect more recent climatic changes—multi-temporal erosion and deposition models based on the USPED protocol are presented.

In line with a growing body of research focusing on the dynamics of recent rural landscapes and on the preservation of historical, cultural, and archaeological heritage in the face of future challenges (Kinnaird et al. 2025; Brandolini et al. 2023)—particularly those posed by climate change—this study aims to highlight two key outcomes.

First, it goes beyond a purely historical understanding of how this mountain environment has been exploited over the past two centuries, addressing instead the evolution of geomorphological processes in relation to changing land-use practices. This approach also makes it possible to highlight the potential relationship between post-depositional phenomena and both the surface and buried archaeological record, encouraging reflection on the meaning, quality, and preservation risks of the evidence emerging from excavation and survey data.

Second, by modelling erosion processes under simulated scenarios that account for the presence or absence of soil-conservation practices—such as terracing supported by dry-stone walls—the research allows for a detailed assessment of the functional effectiveness of these traditional infrastructures, which are now increasingly threatened by neglect and abandonment.

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## 293. Integrating Optical and Radar Remote Sensing to Monitor Urban Sprawl and Assess its Impact on the Ancient Egyptian Cultural Heritage at Bawiti, Bahariya Oasis

*Mina Yacoub (LMU Munich)*

*Nicola Lercari (LMU Munich)*

### 1. Introduction:

Protecting cultural heritage is crucial for preserving collective identity and promoting sustainable development. In Northern Africa and the Middle East, archaeological sites are increasingly threatened by climate change, environmental degradation, and uncontrolled urban expansion, leading to irreversible damage to surface and subsurface archaeological heritage (Lercari et al., 2022). Urban encroachment is a major threat, especially in areas with weak land planning and protection systems (El-Bayomi and Ali, 2015). Advances in remote sensing and geospatial technology now allow efficient monitoring of such impacts (Hagage et al., 2023). Multi-temporal optical imagery supports mapping of land-use and land-cover changes, while Interferometric Synthetic Aperture Radar (InSAR) detects millimetric-scale surface deformation near buried structures. Integrating optical and radar remote sensing within a GIS environment enables long-term analysis of horizontal and vertical transformations in archaeological landscapes. Remote sensing has been widely applied at major Egyptian heritage sites such as Cairo, Giza (Elfadaly et al., 2024), and Luxor. However, these techniques have not yet been utilized to monitor the Bahariya Oasis, in Egypt's Western Desert. This oasis, including the ancient town of Bawiti, is rich in Pharaonic and Greco-Roman remains, which are increasingly affected by modern construction



encroaching on underground rock-cut tombs. This study integrates multi-temporal optical data (Corona, Landsat, Sentinel-2) with Sentinel-1 InSAR analysis to monitor urban sprawl in Bawiti from 1970 to 2025 and assess potential deformation threatening its underground heritage. The results aim to support site management and sustainable conservation of the unique cultural heritage and environment of the Bahariya Oasis.

Case Study:

The Bahariya Oasis, in Arabic: “الواحات البحرية”, and in the ancient Egyptian language: “ ” “wHAt mHyT”, which means “the Northern Oasis,” is one of Egypt’s five major oases in the Western Desert and is situated about 360 km south-west of Cairo. It occupies an area of approximately 2,100 km<sup>2</sup>, lying between the latitudes 27° 48’ and 28° 30’. N, 28° 35’—29° 10’. E, and with mean elevations from about 60 m to 361 m above sea level (Fig. 1). Geologically, it is part of the Nubian Sandstone Aquifer system, one of the largest subterranean water reservoirs in North Africa, with a main bedrock formation of sandstone. The Bahariya Oasis comprises several settlements, including Bawiti, the present administrative center. Human occupation spans from the Middle Palaeolithic to the Greco-Roman period, with notable remains such as the 26th Dynasty tombs of Djed-Amun-ef-Ankh and his son Bannentiu at Qaret Qasr Salim. These fragile monuments now lie within the expanding urban fabric of the modern city. The oasis has seen continuous population growth, driving urban expansion and land-use change, with figures showing an increase of approximately 32.3% from 2007 to 2025 (Egyptian Central Agency for Public Mobilisation and Statistics, or CAPMAS). This consistent demographic increase has intensified urban sprawl, elevating risks to Bawiti’s buried archaeological heritage.

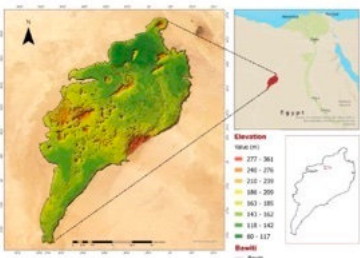


Fig.1: (Right) Map of Bahariya Oasis, showing its location in the Egyptian Western Desert; (Left) Bahariya Oasis' DEM based on SRTM 1-Arc-Second Global.

2. Materials and Methods

This study integrates multi-temporal optical imagery and Interferometric Synthetic Aperture Radar (InSAR) data (Table 1) within a GIS framework to assess urban expansion in Bawiti and its potential impact on nearby cultural heritage sites. All datasets were processed in ArcGIS Pro 3.4, ESA SNAP v13, and Snaphu using the WGS 84 / UTM Zone 35N coordinate system.

Table 1: Multi-sensor satellite data used for monitoring urban expansion and land deformation

| Table 1: Multi-sensor satellite data used for monitoring urban expansion and land deformation |                   |                       |                                 |                     |
|-----------------------------------------------------------------------------------------------|-------------------|-----------------------|---------------------------------|---------------------|
| Number                                                                                        | Satellite Mission | Sensor                | Acquisition Date                | Data Source         |
| 1                                                                                             | Corona            | KH-4B                 | 29 July 1970                    | CAST                |
| 2                                                                                             | Landsat-5         | TM (Collection 2, L2) | 4 November 1995                 | USGS Earth Explorer |
| 3                                                                                             | Landsat-5         | TM (Collection 2, L2) | 5 November 2005                 | USGS Earth Explorer |
| 3                                                                                             | Sentinel-2        | MSI (L1C)             | 24 November 2015                | Copernicus Browser  |
| 4                                                                                             | Sentinel-2        | MSI (L2A)             | 27 October 2025                 | Copernicus Browser  |
| 5                                                                                             | Sentinel-1A       | IW_SLC (VV/VH)        | 09 October and 14 November 2015 | Copernicus Browser  |
| 6                                                                                             | SRTM              | 1-Arc Second DEM      | 22 September 2014               | USGS Earth Explorer |

2.1. Optical Satellite Data Analysis

Multi-temporal imagery from Corona (1970), Landsat 5 TM (1995, 2005), and Sentinel-2 (2015, 2025) was analysed to detect land-use and land-cover changes over five decades. The Corona image (29 July 1970) was orthorectified and reprojected to correct geometric distortions and ensure alignment with later datasets; its urban area was manually vectorised. Sentinel-2 Level-



1C data were processed with Sen2Cor to generate Level-2A surface reflectance products corrected for atmospheric and illumination effects, then enhanced using Sen2Res for improved spatial quality. All Sentinel-2 data were resampled to 30 m to match Landsat resolution for pixel-based comparison. Supervised Classification was performed using a Support Vector Machine (SVM) with three land-cover classes—Urban, Barren, and Vegetation (Fig. 2)—to map spatial patterns of urban sprawl over known archaeological zones.

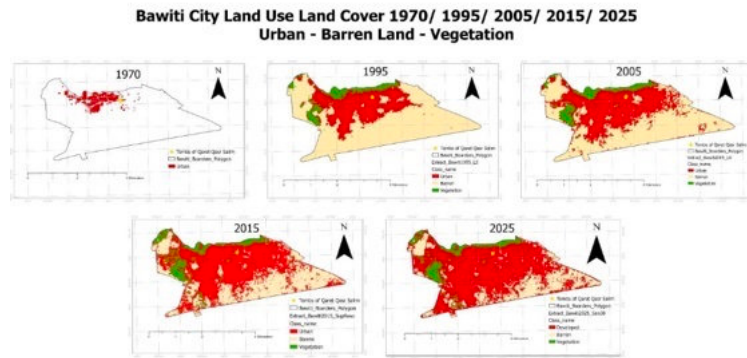


Fig.2: Multi-temporal LULC maps of Bawiti City (1970–2025) showing the progressive expansion of urban areas, reduction of barren land, and a slight increase in vegetation over time.

## 2.2. InSAR Data Processing

To detect surface deformation that could threaten underground tombs, we processed Sentinel-1A IW SLC (VV/VH) data in SNAP using a customised interferometric workflow for 14 and 26 November 2015 (12-day interval). This baseline preserved radar phase consistency and high coherence, allowing millimetric deformation detection (Fig. 3). In the Read step, the 14 November Sentinel-1 SLC was set as the master in native Sentinel-1 format. TOPSAR-Split was set to Subswath IW1, Polarisation VV, and Bursts 6–7 covering Bawiti. The 26 November SLC served as the slave, using identical subswath, polarisation, and burst settings for spatial consistency (Fig.3).



Fig.3: Our workflow of Sentinel-1A InSAR processing in SNAP, showing sequential steps from data reading and orbit correction to interferogram generation, filtering, and deformation map output.

Both datasets underwent orbit refinement using the Apply-Orbit-File tool with Sentinel Precise Orbit Ephemerides (Auto Download) and a polynomial degree of 3. Back-Geocoding applied the SRTM 1Sec\_HGT (Auto Download) DEM with bicubic interpolation to enhance elevation accuracy. The Enhanced Spectral Diversity operator ran with default settings, and the interferogram was generated using a  $20 \times 6$  (range  $\times$  azimuth) window. After TOPSAR-Deburst, TOPPhaseRemoval, and Multilooking, Goldstein Phase Filtering was applied. Phase unwrapping was performed in Snaphu (deformation mode) using the Minimal Cost Flow Algorithm, then converted to displacement, terrain-corrected, co-registered, and filtered to remove low-coherence pixels.

## 3. Preliminary Results and Discussion

Our analysis of multi-temporal satellite imagery reveals rapid urban growth in Bawiti. We used Support Vector Machine classification of Landsat (1995, 2005) and Sentinel-2 (2015, 2025) datasets, while manually digitizing the Corona data (1970) to obtain distinct urban, vegetation, and barren land classes. The Bawiti administrative area covers about 12.821 km<sup>2</sup>, with built-up land increasing from 0.822 km<sup>2</sup> in 1970 to 8.358 km<sup>2</sup> in 2025 (Table 3), representing more than a tenfold expansion over 55 years. This growth reflects rising population, infrastructure development, and agricultural expansion, mainly around the historical core to the east and south, with limited expansion westward into cultivated and archaeologically sensitive zones.

**Table 3:** Multi-temporal urban area calculations.

| Year | Satellite Mission | Classification Method  | Urban Area (km <sup>2</sup> ) | % of 2025 Urban Extent | % of Core City (12.821) |
|------|-------------------|------------------------|-------------------------------|------------------------|-------------------------|
| 1970 | Corona            | Digitisation           | 0.822                         | 9.8%                   | 6.4%                    |
| 1995 | Landsat-5         | Support Vector Machine | 3.576                         | 42.8%                  | 27.9%                   |
| 2005 | Landsat-5         | Support Vector Machine | 5.101                         | 61.0%                  | 39.8%                   |
| 2015 | Sentinel-2        | Support Vector Machine | 6.642                         | 79.5%                  | 51.8%                   |
| 2025 | Sentinel-2        | Support Vector Machine | 8.358                         | 100%                   | 65.2%                   |

Interferometric analysis of Sentinel-1A data (09 October – 14 November 2015) produced coherent interferograms, enabling accurate phase unwrapping. The displacement map revealed vertical shifts of -8 mm of land subsidence, primarily along the urban–agricultural edge, indicating minor subsidence likely caused by increased groundwater-induced soil compaction. Combined optical and radar data suggest that shallow groundwater rise and ground instability are degrading Bawiti’s archaeological heritage, especially near new developments. Future time-series InSAR (SBAS/PSI) and hydrogeological analyses will refine long-term deformation assessment and support a Cultural Heritage Vulnerability Map for sustainable land use and heritage protection in the Bahariya Oasis.

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### 304. Annual-scale soil erosion monitoring using high-resolution UAV-collected DEMs at the Medieval Silk Road settlement of Ak-Beshim, Kyrgyzstan

*Patrick Cuthbertson (Central Asian Archaeological Landscapes Project (CAAL), UCL; Centre for the Archaeology of Human Origins (CAHO), University of Southampton)*

*Gai Jorayev (University College London (UCL), Macao University of Tourism)*

*Marco Nebbia (University College London (UCL))*

The site of Ak-Beshim (formerly medieval ‘Suyab’) is located within the Kyrgyz extent of the Chuy Valley in the northern Tien Shan range. The settlement was initially founded sometime around the 5th- 6th centuries, possibly as a trading post, and later enclosed with fortifications and occupied for between five and six centuries (Clauson 1961: 4). While relatively isolated, it comprised one of a number of strategically-important fortified towns in the northern extent of the Silk Road around the Tien Shan mountains, weathering the varying fortunes of several empires in the region (Abe 2014: 11-12; Clauson 1961: 5). The area of the remains of the town can be approximately divided into three distinct features: a very visually-prominent Shakhristan with substantial fortifications of unbaked mudbrick (~35 ha), a citadel situated in the southwestern corner of the Shakhristan, and the Rabad (~60 ha) with less substantial fortifications to the south-east of the Shakhristan.

Ak-Beshim has attracted the attention of scholars since at least the late 19th century, and been subject to regular archaeological investigation and

excavation throughout the 20th century (Clauson 1961: 1–2). However, the surviving surface remains of the fortified town are potentially under active threat of destruction in their present situation. As well as generalised environmental risks, the area surrounding and inclusive of the former medieval settlement is also a working agricultural landscape with both arable and pastoral agriculture being practised. Our aim in the present study has been to assess the rate of soil erosion and morphological change on the visible remains in order to properly assess these risks to the preservation of the site, as well as to provide results that could be used to inform regional and national heritage preservation policy for Ak-Beshim and similar sites. Further to this, we had the goal of creating a more automated workflow, which would be both replicable and generalisable for application in other, similar scenarios with surviving surface remains.

Our approach has been developed using high-resolution Digital Elevation Models (DEMs), which were captured annually via Unmanned Aerial Vehicle (UAV/drone) over several seasons of fieldwork accompanying the ongoing Kyrgyz-Japanese excavation at Ak-Beshim. These were captured over a four-year period from 2022–2025. Our goal has been to identify annual-scale rates of change where possible, equating to processes of soil erosion and accumulation at Ak-Beshim, thus enabling a high-precision approach to monitoring risk to the monument. Remote sensing applications for the assessment of soil erosion, landscape change, and heritage risk can potentially operate at lower resolutions, using elevation data and processed DEMs captured via satellite. While such approaches are effective for detecting longer-term, higher-level landscape changes (for instance, wider landscapes at a decadal scale), they would not be appropriate for identifying annual rates of change at the scale of a site such as Ak-Beshim in its immediate landscape. Furthermore, a quantitative approach is to be preferred over qualitative approaches to soil erosion assessment and change detection because it can more precisely determine the impact and extent of erosion, can help link local variations in erosive change more concretely to wider prevailing conditions, and

will allow for stricter comparisons to be made when the method is applied to further sites in different landscapes.

This approach has also entailed tackling a number of challenges, many of which are shared with lower-resolution approaches to landscape change detection but are further compounded in a higher-resolution approach. The high resolution of the DEMs has required careful processing to remove as much interference as possible. Accurate alignment of the DEMs is especially important at this scale, and is difficult to achieve from year to year without robust ground control points. Vegetation also provides a lot of interference, varying in extent and density from year to year. Finally, some interference to change detection is inevitable in areas where active excavation has been taking place during data collection. All of these represent challenges for manual processing, but provide particularly substantial challenges to the automation of the modelling process in a more automated workflow. We tested a number of methods, including simple difference surfaces, change layer (as per Rayne et al. 2020: Equation 1), and the Revised Universal Soil Loss Equation (RUSLE). Initial results are promising, with relatively small features identifiable between different years, and visible changes in the landscape detectable. We will present the results of this change detection and erosion risk modelling at Ak-Beshim over the years the DEMs were captured, and detail how we tackled the challenges in its execution.

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### 339. Unmanned Aerial Vehicle (UAV) Photogrammetry for Archaeological Documentation: A Case Study of Shahr-i Zohak, Afghanistan

*Masood Zaman (Qayoom Ihsan Limited)*

This study presents an innovative approach to surveying and monitoring archaeological sites in conflict/post-conflict zones using Unmanned Aerial Vehicles (UAVs). The fortified citadel of Shahr-i Zohak, a UNESCO World Heritage Property in Bamiyan, Afghanistan, serves as a case study. We discuss the strategies and methodologies employed to create a 3D model of the site, addressing challenges such as limited accessibility, UXO presence, and data connectivity issues. Our results demonstrate the effectiveness of using Skydio's X10 and S2 drones, achieving 3D models with an average accuracy of 1 millimeter per pixel. This research highlights the capabilities and limitations of UAV-based photogrammetry in challenging environments, providing practical guidelines for future applications.

**Keywords:** Aerial archaeology, UAV photogrammetry, conflict zones, cultural heritage preservation, Shahr-i Zohak, Bamiyan, Afghanistan

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### 439. Satellite-based Monitoring of Urban and Environmental Threats to the Lebanese Cultural Heritage: A Decade of Change at the Bronze-Age Site of Tell Fadous-Kfarabida

*Georgios Leventis (ERATOSTHENES Centre of Excellence)*

*Mahmoud Mardini (ERATOSTHENES Centre of Excellence)*

*Hermann Genz (American University of Beirut)*

Archaeological and cultural heritage sites are often located in regions susceptible to various risks that originate either from man-made activities (urbanization, looting, etc.), or environmental associated factors (salinity, heat events, dust, etc.) or a combination of those. The progress of such risks assists in the extensive destruction of archaeological sites and historical monuments. The integration of remote sensing technologies enables researchers and policymakers to assess damage, document changes, and develop proactive conservation strategies, thereby highlighting the importance of cultural heritage in fostering social cohesion, economic growth, and environmental sustainability [1]. Satellite imagery has been crucial in documenting these damages, providing a "before and after" analysis that highlights the extent of destruction and aids in the planning of restoration efforts. Their exceptional spatial detail and multispectral capabilities, allow for the visualization of features that may be obscured by clouds, vegetation, or nighttime conditions.

The case study focuses on the archaeological mound of Tell Fadous-Kfarabida, located about 2 km south of the modern town of Batroun, within the village of Kfarabida on the northern Lebanese coast [4-5]. The tell originally covered around 1.5 hectares (ca. 140 × 105 m) and is bordered by a steep drop to Wadi Bou Aaoun on the north and the Mediterranean Sea on the west [4-5]. To the south and east, traces of fortification walls indicate that the settlement was once enclosed. Excavations revealed occupation primarily during the Early Bronze Age II–III, when the site functioned as a small coastal town devoted to agriculture and fishing, with domestic structures,

craft activity, and both local and regional trade connections [4–5]. Modern damage has been severe: parts of the tell were destroyed in the 1940s by the construction of the coastal road and later by a railway line, while additional bulldozing in recent decades removed sections for cement production, ironically exposing valuable stratigraphy [4]. In 2025, another bulldozing incident leveled part of the 5,000-year-old mound during private land development, prompting public outcry and renewed demands for site protection [6]. Ongoing urban expansion, unregulated construction, and environmental risks continue to endanger the surviving archaeological strata, making Tell Fadous-Kfarabida a good case-study for satellite-based monitoring and multi-hazard risk assessment of vulnerable coastal heritage.

The integration of time-series analysis with satellite imagery in this work enhances the understanding of how risks evolve over time. By analyzing data collected across different temporal intervals, we can track changes in environmental conditions, urban development [2], and assess possible damage patterns to the site, providing insights into the ongoing vulnerabilities faced by cultural heritage sites [3]. For the abovementioned case study, we collected satellite imagery from Planet ; PlanetScope imagery with resolution of 3m. covering a 10-year period from November 2015 to November 2025 and SkySat imagery with resolution 0.5m for validation purposes as their higher resolution aids us to better understand the environmental stresses for smaller scale archaeological sites. The latter covers a smaller period due to the availability of data. The data collection part is complemented by Sentinel 2 and Sentinel 3, focusing specifically on winter and summer periods to interpret seasonal variations. Using data fusion techniques on the above sources, we generated risk indices that provide more accurate and comprehensive information on the stresses (both man-made and environmental) that are apparent on the Lebanese site.

The framework presented in this study constitutes a significant part in the monitoring and risk assessment of cultural heritage sites related to natural hazards and anthropogenic pressures. The increasing frequency of destructive events has highlighted the necessity for effective and efficient monitoring systems that can provide timely data on the condition and changes in

archaeological and cultural heritage sites, that can be exploited for effective management and preservation strategies, hence allowing stakeholders to respond proactively to emerging threats.

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## S43: Digital Evolution in Archaeological Practice: From Innovation to Infrastructure and FAIR data

*Chiara G. M. Girotto, Freelance Archaeologist & Osteologist*

*Daniel Löwenborg, Uppsala University*

*Albrecht M. F. Knauber, Arch Pro Beratungsgesellsch. mbH*

*Stephan Winkler, illisystems*

**Location:** Franz König Saal

**Session Format:** Standard

Following recent explorations of the implementation of standards, FAIR data recording, and emergent standards, as well as their intersection with commercial archaeology and academic research, this session examines the development lifecycle of digital archaeological data and solutions—from experimental tools to essential infrastructure. We wish to investigate how innovations become integrated into archaeological practice and what this evolution reveals about the discipline's digital future.

Commercial archaeology occupies a unique position where innovation must prove itself immediately practical. This session explores the development pathways of digital solutions, examining how tools evolve from addressing specific project needs to serving broader archaeological communities, and can navigate both formal organisational requirements and the needs of academic research. We invite papers that explore the critical transition points where individual solutions become shared resources, and local innovations gain international relevance.

The session addresses the increasingly blurred boundaries between commercial and academic data generation. As development-led archaeology produces ever-larger datasets structured according to FAIR principles, these resources become invaluable for synthetic research, regional studies, and heritage management. We examine how this convergence shapes development priorities and funding models for archaeological infrastructure. This

becomes increasingly relevant as the EU Open Data Directive is implemented, and there will be growing pressure to make data from archaeological investigations openly accessible and FAIR. By building on solutions from the archaeological community, this can be an opportunity to transform archaeological practice.

Central to our discussion is the sustainability of digital innovation. Many successful solutions begin as cost-effective responses to immediate needs—custom scripts, adapted open-source tools, or lightweight databases. We explore how these pragmatic beginnings can evolve into robust, maintainable systems without losing their original flexibility and efficiency.

The human dimension remains paramount: how do development teams strike a balance between user needs and technical possibilities? How do we ensure that digital evolution enhances rather than constrains archaeological practice? What governance models best support community-driven development while ensuring long-term sustainability?

We invite contributions addressing:

- Challenges in scaling local solutions to international contexts
- Development trajectories from prototype to production in archaeological software
- Governance models for community-driven digital infrastructure
- Bridging commercial innovation with academic research needs
- Sustainability strategies for archaeological digital tools and data
- The economics of open-source development in archaeology
- User-centered design in archaeological software development
- Case studies of successful tool evolution and adoption

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**08:30 –  
08:50**

42. From Innovation to Implementation: A Case Study in Researcher and End-user Collaboration to Create Usable Imaging Tools

*Samantha Porter\*; Katrina Yezzi-Woodley\*; Riley C. W. O'Neill\*; Jeff Calder\*; Peter J. Olver\**

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*\*University of Minnesota*

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|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>08:50 – 09:10</b> | 54. From Data Fragmentation to Knowledge Graph: Archipel as a FAIR Digital Infrastructure for Preventive Archaeology in France<br><i>Kai Salas Rossenbach (Inrap)</i>               |
| <b>09:10 – 09:30</b> | 71. What professional infrastructure does an excavation company need?<br><i>Albrecht Knauber (Arch Pro Beratungsgesellschaft mbH)</i>                                               |
| <b>09:30 – 09:50</b> | 74. Migration and Integration of CAD-based Excavation Documentation into an Archaeological GIS Framework: A Case Study from Manching, Bavaria<br><i>Christoph Danner (Pro Arch)</i> |
| <b>09:50 – 10:10</b> | 77. Integration of Work- and Billing-Relevant Metadata into GIS-Based Archaeological Documentation<br><i>David Biedermann (Pro Arch Prospektion und Archäologie GmbH)</i>           |
| <b>10:10 – 10:30</b> | 101. Standardizing Color Documentation in Archaeology: Using Digital Tools and Reference Palettes for Consistent Field Recording<br><i>Carolina de Bruyne (Pro Arch)</i>            |
| <b>10:30 – 11:00</b> | Coffee break                                                                                                                                                                        |
| <b>11:00 – 11:20</b> | 207. Managing Complexity: A Digital Management System for Experimental Archaeology                                                                                                  |

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*Syed Ghaus Rabbani (Leibniz Zentrum für Archäologie (LEIZA)); Ivan Calandra (Leibniz Zentrum für Archäologie (LEIZA))*

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|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>11:20 – 11:40</b> | 215. A GIS-Enabled Application for Bayesian Optimal Allocation of Effort in Archaeological Surveys<br><i>Edward Banning (University of Toronto); Steven Edwards (Nova Scotia Community College)</i>                                                                                                                                                                                   |
| <b>11:40 – 12:00</b> | 248. The CUD of an Archaeologists' Guide to Good Practice: Bridging Innovation and Infrastructure in Digital Stratigraphic Analysis<br><i>Keith May (Historic England); James Taylor (University of York)</i>                                                                                                                                                                         |
| <b>12:00 – 12:20</b> | 350. From Prototype to Standard – Digital Transformation from Innovative Tool to Added Value?<br><i>Stephan Winkler (illisystems); Nathalie Rodriguez (LWL-Archäologie für Westfalen)</i>                                                                                                                                                                                             |
| <b>12:20 – 12:40</b> | 381. From 16 to One - The attempt to create a uniform German data model<br><i>Anna Anzenberger (Illisystems); Stephan Winkler (Illisystems)</i>                                                                                                                                                                                                                                       |
| <b>12:40 – 13:00</b> | 405. RADOGOST archaeological repository: building a FAIR, interoperable archaeology data service<br><i>Arkadiusz Sołtysiak (University of Warsaw); Marcin Maciejewski (Maria Curie-Skłodowska University); Julia Chyla (University of Warsaw); Wojciech Fenrich (ICM UW); Kamil Filippek (Maria Curie-Skłodowska University); Łukasz Dumiszewski (ICM UW); Łukasz Bownik (ICM UW)</i> |
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## 42. From Innovation to Implementation: A Case Study in Researcher and End-user Collaboration to Create Usable Imaging Tools

*Samantha Porter (University of Minnesota)*

*Katrina Yezzi-Woodley (University of Minnesota)*

*Riley C. W. O'Neill (University of Minnesota)*

*Jeff Calder (University of Minnesota)*

*Peter J. Olver (University of Minnesota)*

The growing sophistication of the use of imaging technology in archaeology underscores the need for research tools that are not only powerful, but approachable. This requires building usable infrastructure for sharing these tools that follows FAIR principles - findability, accessibility, interoperability, and reusability. Here we present, as a case study, the efforts of a collaboration between a research team creating innovative code-based imaging tools, and a University digitization center who is actively implementing those tools. We show how computationally-rooted research teams can collaborate with other groups to make their work more accessible to a broader audience.

AMAAZE-labs is a research team of archaeologists, computer scientists, and mathematicians that has recently developed Python-based semi-automated surfacing tools to rapidly create 3D models of items scanned in bulk using micro-CT or CT scan data (O'Neill et al. 2024, Yezzi-Woodley et al. 2022). These protocols enable research-quality 3D digitization of thousands of fragments with minimal human intervention (less than 10 minutes per scan, each of which can contain over a hundred specimens). These protocols were made freely available on GitHub with the goal of making it easier for researchers (within and beyond archaeology), museums, and other institutions to digitize their large collections more efficiently. However, many of the teams that

could benefit from these tools may have limited or no experience with Python, which can be a prohibitive factor. As 3D imaging continues to accelerate in archaeology, tool development often outpaces documentation and thus usability. Further, those who develop these tools often become fluent in their technical language and workflows, making it easy to forget, or never fully learn, how to translate them for different audiences. This coupled with the fact that many researchers and collections specialists encounter technical, psychological (e.g. intimidation by code-based workflows), and resource barriers limit uptake.

The Advanced Imaging Service for Objects and Spaces (AISOS) is an imaging center at the University of Minnesota that provides digitization services to the entire University community. Its researchers have extensive experience in 3D scanning using photogrammetry, LiDAR, and structured-light scanning, but limited experience with CT scanning and coding. AISOS has been fielding increasing requests from faculty and graduate students for bulk 3D scanning. AISOS is working toward employing the AMAAZE en masse scanning and post-processing protocols to assist other research teams with their 3D digitization needs. Though AMAAZE's open-source surfacing tool offers an elegant solution to what would otherwise be incredibly demanding of time and resources using other methods, AISOS quickly encountered challenges operationalizing the tool. Conceptually, the 3D data aspect of the AMAAZE protocol is well within the domain expertise of AISOS, however, the Python-based post-processing as initially shared by AMAAZE, presented the aforementioned challenges. These ranged from not knowing how to install required packages, to not being able to quickly change hard coded file paths, to not recognizing that the code as initially shared was written for a different operating system. Through a series of meetings and workflow trials, we collectively established an iterative feedback process in which AMAAZE trained AISOS on their protocols, then AISOS tested AMAAZE protocols, identified usability pain points, and proposed revisions that would enable wider adoption of these tools across disciplines.

This collaboration grew out of a shared recognition that technical innovation alone does not ensure impact. Thus, AMAAZE and AISOS are working closely together to transform the ways in which these protocols are shared publicly to create more inviting inroads for others to use these tools. Our hope is that, at minimum, the lessons we learned and share here will be useful to other research teams who are innovating in the field, and perhaps, this will inspire other similar collaborations between developers and end-users.

O'Neill, R. C., Yezzi-Woodley, K., Calder, J., & Olver, P. J. (2024). En masse scanning and automated surfacing of small objects using Micro-CT. arXiv preprint arXiv:2410.07385.

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## 54. From Data Fragmentation to Knowledge Graph: Archipel as a FAIR Digital Infrastructure for Preventive Archaeology in France

*Kai Salas Rossenbach (Inrap)*

Inspired by the ARIADNE experience and by European efforts to make archaeological data more open, connected, and reusable, Archipel (<https://archipel.inrap.fr>) represents France's first large-scale attempt to turn preventive archaeology's massive documentation into a coherent, FAIR-aligned knowledge infrastructure. Launched in 2025 by the French National Institute for Preventive Archaeological Research (Inrap), the platform links together more than 50,000 excavation reports, 16,000 publications, 2,000 research projects, and extensive geospatial datasets within a single semantic framework.

Preventive archaeology in France generates an enormous quantity of structured data, yet much of this information has historically remained fragmented across distinct institution's repositories. Archipel addresses this challenge by connecting Inrap's main scientific systems—DOLIA (archaeological operations), CAVIAR (spatial data), HAL-Inrap (publications), and AGIR (research projects)—as well as the scientific profiles of over 4,000 archaeologists. Using a CIDOC-CRM-based ontology, the platform builds a navigable knowledge graph of preventive archaeology, allowing users to explore relationships between operations, researchers, publications, and projects.

Developed jointly by Inrap's Scientific and Technical Directorate (DST) and Information Systems Directorate (DSI), Archipel is supported by France's Fonds pour la Transformation de l'Action Publique (FTAP), under the supervision of the Direction interministérielle de la transformation publique (DITP) and the Direction interministérielle du numérique (DINUM). The project has been designed and implemented with three key partners: Probabl (semantic search and data science), Reciproque (UX design and interoperability), and the Foundation for Research and Technology – Hellas (FORTH), the originator of the CIDOC-CRM ontology, which provides methodological support for semantic modelling and long-term interoperability.

Beyond its technical architecture, Archipel represents a conceptual and institutional shift: from managing archaeological documents to managing archaeological knowledge. By linking fieldwork data to research outputs and professional expertise, the platform aligns operational, administrative, and scientific dimensions within a unified open-data environment. It redefines the role of preventive archaeology—not merely as a regulatory practice, but as a continuous producer of reusable, verifiable scientific information.

Archipel's design embodies the principles of open science and public value, making it both a national and European contribution to the implementation of the EU regulations and objectives. By providing open access to metadata and semantic relationships, the platform enhances transparency, encourages data citation, and enables synthetic research on a scale previously impossible in French archaeology.

Situated at the intersection of heritage management, digital humanities, and data governance, Archipel builds upon ARIADNE's European vision while adapting it to the realities of large-scale preventive archaeology. It offers a replicable model for other public research institutions seeking to transform dispersed operational datasets into durable, FAIR digital infrastructures. Ultimately, Archipel demonstrates that digital innovation in archaeology extends beyond technology: it is about creating shared frameworks of meaning and accountability that make archaeological knowledge collectively usable, comparable, and sustainable across borders and generations.

## 71. What professional infrastructure does an excavation company need?

*Albrecht Knauber (Arch Pro Beratungsgesellschaft mbH)*

What kind of infrastructure does a professional excavation company need in modern times? How must these companies organize themselves, what compliance requirements must they consider – both in regard to client expectations and legal regulations – and what technologies are essential for long-term success?

Compared to the workflows of past decades, excavation companies today face a growing number of inputs from diverse fields and sources.

The demand of archaeological excavation companies have often only fit partially into fully digitalized and professional software solutions. There is currently no comprehensive, integrative system that captures all aspects of archaeological work within a single application. Excavation companies are no longer solely focused on fieldwork – their role has expanded significantly. The work environment is constantly evolving and being reshaped by technological and organizational change.

Mid-sized companies in particular face a high demand for standardized and simplified processes in order to increase efficiency, improve results, reduce costs, and remain competitive. As a result, many tasks are shifting – from

paper to screen, and increasingly from isolated systems to connected digital services and routines.

On this path, companies face a variety of challenges – including software life cycles, outdated systems, and the impact of collaboration with other excavation companies on decision-making around workflows and data exchange. Especially when working in partnerships, companies must align on methods and ensure data is exportable or migratable, even if the technical decisions are made unilaterally.

This talk explores what is needed for the successful transformation to a modern digital infrastructure using a practical example, focusing on communication channels and organizational structures. The goal is to spark a discussion about the real necessity's excavation companies face in improving their performance through digital infrastructure management – ultimately enabling the creation of FAIR-data. It is no longer a 'nice-to-have', but a fundamental requirement. Before we can create FAIR data, we must build "FAIR infrastructure".

## 74. Migration and Integration of CAD-based Excavation Documentation into an Archaeological GIS Framework: A Case Study from Manching, Bavaria

*Christoph Danner (Pro Arch)*

### Introduction

In recent decades, digital technologies have profoundly transformed archaeological documentation. While Computer-Aided Design (CAD) has long served as the standard for recording excavations, the rise of Geographic Information Systems (GIS) has opened new possibilities for spatial analysis, data integration, and interdisciplinary collaboration. However, the transition from CAD-based workflows to GIS-driven systems remains technically and conceptually challenging (Samih Al Rawashdeh Balqies Sadoun and Akif Al Fukara 2012), especially for institutions managing legacy excavation data.

This paper presents the methodology, implementation, and evaluation of a data migration and integration workflow developed for an archaeological excavation in Manching (Bavaria, Germany). The project aimed to convert a large, complex CAD dataset containing excavation plans, measurement data, and contextual information into a fully functional GIS environment. The central research question addressed was how legacy excavation documentation - originally structured for CAD visualization - can be effectively transformed and integrated into a GIS while preserving data integrity, spatial accuracy, and archaeological meaning.

The study also explores whether GIS can replace CAD as the primary tool for plan creation, data management, and analytical evaluation in archaeological projects. Beyond the case study, the results contribute to broader discussions on digital transformation in archaeology and the use of open-source tools for sustainable data management.

#### Methods and Materials

The dataset originated from a large-scale excavation between 2021 and 2024 in the area of the B16 near Manching, a La Tène-period oppidum dating from the 3rd to 1st centuries BCE. The CAD master plan included over one thousand measurement jobs recorded using GNSS instruments, each containing multiple layers representing finds, features, and excavation boundaries.

The initial step involved the development of a UML data model to define the logical structure of archaeological entities and their relationships. This model provided the foundation for designing GIS layers with appropriate geometry types and attribute schemas. Separate layers were created for survey nails, finds (points), profiles (lines), and archaeological structures such as features, tree throws, and disturbances (polygons).

Data preparation focused on closing open polylines, creating hatches for features, and standardizing layer names in CAD software. Extended object data

("XData"), containing metadata such as surveyor IDs, job IDs, and measurement dates, were extracted by a Python-based automation tool. By using the "win32com" and "pandas" libraries, it established a direct connection with AutoCAD. This script iterated through all relevant layers, identified entities based on type and naming conventions, extracted coordinates and attributes, and exported them into structured CSV files.

Subsequently, the data were imported into QGIS as GeoPackage (.gpkg) layers using a custom-built interface. GeoPackages were chosen over shapefiles due to their superior handling of long attribute names, higher storage capacity, and built-in styling options (Open Geospatial Consortium 2024). Additional materials integrated into the GIS included Excel-based context lists, Access databases documenting finds, and photographic records of stratigraphic profiles.

#### Results

The migration successfully converted all relevant CAD data into a consistent GIS schema. The resulting QGIS project included over 144 active layers organized by excavation planum, geometry type, and archaeological feature category. In comparison the original CAD file included up to 500 different layers. After iterative quality checks and corrections, nearly all relevant datasets were successfully migrated, with minor attribute gaps limited to legacy files lacking the extended object data.

A comprehensive geometry and topology validation was conducted using QGIS's built-in tools. Errors such as self-intersecting polygons, overlapping geometries, and duplicate points were identified and corrected. This process not only improved spatial data quality but also exposed recurring issues in the original CAD datasets—such as inconsistent line closures and redundant point entities—that had previously gone unnoticed.

Advanced symbolization and rule-based visualization were implemented to replicate the cartographic conventions of the original CAD plans while

enhancing interpretability. Each material category (e.g. iron, ceramics, bone) received a specific color scheme, and archaeological structures such as pits, ditches, and postholes were represented through semi-transparent polygons with distinctive fill patterns. The resulting GIS maps maintained the familiar aesthetic of the CAD drawings but gained analytical depth through interactive querying, spatial joins, and filtering functions.

The integration of external datasets—such as stratigraphic descriptions (“Be-fundansprache”) and profile images—enabled a multidimensional representation of excavation contexts. Users are now able to click on individual features to access related lists, photographs, and measurements, thus linking spatial and descriptive information in a single environment.

#### Discussion

The migration process demonstrates that GIS can serve as a full replacement for CAD in archaeological documentation, provided that data models and workflows are carefully adapted. The transition yielded several advantages:

1. Enhanced analytical capabilities – Spatial relationships between finds and features can now be explored through buffer analyses, density mapping, and visibility studies, extending the interpretive potential beyond static plans.
2. Integrated data management – The unification of spatial and non-spatial datasets within a single GeoPackage provides enhanced data overview and management, thereby simplifying updates, improving data consistency, and ensuring long-term archiving.
3. Interoperability and scalability – By employing open-source tools such as QGIS and Python, the workflow is easily replicable, cost-effective, and compatible with broader research infrastructures.

Nevertheless, challenges remain. The heterogeneity of legacy CAD datasets—often lacking standardized attributes or consistent geometry—

requires extensive manual preprocessing. Furthermore, staff training in GIS principles is essential to ensure proper data handling and prevent semantic errors during interpretation.

From a broader perspective, the study illustrates how digital transformation in archaeology can bridge disciplinary boundaries between geomatics and archaeological sciences. The collaboration between geodesists and archaeologists at Pro Arch GmbH not only improved data quality but also fostered new understanding of how spatial technologies shape archaeological reasoning.

Ultimately, the results contribute to a growing body of research emphasizing the importance of data modeling, interoperability, and sustainable digital preservation in cultural heritage management.

The GIS created through this project now serves as a working prototype for future excavation documentation within the company. Its modular design and standardized schema allow for continuous expansion, including the integration of photogrammetric models and 3D spatial data. The approach may serve as a blueprint for other institutions and organizations seeking ways to modernize their archaeological documentation workflows while preserving the interpretive richness of legacy datasets.

#### Keywords:

CAD - GIS – excavation documentation – data modeling – data migration

#### References

Samih Al Rawashdeh Balqies Sadoun, and Akif Al Fukara. 2012. “CAD File Conversion to GIS Layers: Issues and Solutions.”

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<https://www.ogc.org/standards/geopackage>.

## 77. Integration of Work- and Billing-Relevant Metadata into GIS-Based Archaeological Documentation

*David Biedermann (Pro Arch Prospektion und Archäologie GmbH)*

The increasing complexity of archaeological excavations, particularly in rescue and development-led contexts, requires digital infrastructures capable of integrating both scientific and administrative requirements. In addition to the precise recording and analysis of features, finds, and documentation processes, work-related and billing-relevant metadata have become essential. Such metadata include information on which staff members worked on specific excavation units at given times, which documentation steps were performed, and which tasks were authorized by whom.

This project (which is in most parts work in progress) examines the integration of all relevant excavation data within a GIS-based information system. The objective is to structure archaeological documentation in a coherent relational data model that simultaneously supports scientific recording and administrative workflows. QGIS is employed as the platform to manage spatially-referenced data, temporal sequences, and personnel information in a structured and linked manner. Excavation layers, profiles, finds, plans, photographs, and drawings are modeled as digital objects, each associated with metadata describing work dates, responsible staff, executed tasks, and approvals. The inclusion of these metadata enables comprehensive process traceability and facilitates the automated generation of performance and billing summaries.

The underlying database structure is relational and designed to ensure both consistency and traceability. All changes to data records are logged and version-controlled. Interoperability with common formats (CSV, XML, shapefile,

geodatabase, PDF) is ensured to allow internal and external use. A key feature is the explicit linkage of spatial, temporal, and personnel information, allowing every workflow step to be modeled as an event in a space-time diagram. This approach provides both operational transparency and the ability to evaluate process efficiency.

Integrating work-related metadata into archaeological documentation raises questions regarding data protection, purpose limitation, and legal compliance. The system is designed so that personal information is recorded only as necessary for work or billing purposes. After project completion, anonymization of personal data is implemented, and access rights are role-based. Engagement with regulatory authorities is being pursued to establish guidelines ensuring that technical records of "who did what, where, and when" remain confined to datasets already required for legal or billing purposes. Such harmonization balances scientific transparency, administrative necessity, and data protection requirements.

The implementation of a GIS-based system with integrated personnel and task tracking facilitates quality assurance, resource management, and process traceability. It also provides the foundation for developing standardized procedures, allowing digital archaeological documentation to be consistent, verifiable, and legally compliant. The planned pilot phase will evaluate functionality and usability on active excavation projects. Anticipated benefits include improved administrative efficiency, enhanced data integrity, and the ability to produce detailed statistical reports for project management and billing. Furthermore, the system serves as a basis for advancing digital standards in archaeological practice, meeting both scientific and regulatory demands.

In conclusion, harmonizing technical and administrative data in archaeological information systems, while respecting data protection and ensuring process traceability, is essential for responsible digital practice. This contribution presents the conceptual framework, structural considerations, and legal context of a GIS-based documentation system and encourages discussion on how digital archaeology can be conducted efficiently, transparently, and in compliance with legal and ethical standards.

## 101. Standardizing Color Documentation in Archaeology: Using Digital Tools and Reference Palettes for Consistent Field Recording

*Carolina de Bruyne (Pro Arch)*

### Introduction

Accurate color recording is an essential part of archaeological field documentation, particularly for soil layers, features, and artifacts. Traditionally, archaeologists rely on manual color representation, often using high-quality drawing materials such as Faber-Castell Polychromos pencils, which ensure light resistance and long-term archival durability. However, color perception is inherently subjective and can vary depending on lighting conditions, individual perception, and the materials used, potentially limiting the reproducibility and comparability of documentation across excavations. To address these challenges, this project explores the integration of digital color identification methods with traditional documentation techniques to improve consistency, objectivity, and interoperability in archaeological color recording.

### Methods and Materials

The initial approach tested a color-scanning device that provided approximate color matches with corresponding HEX values. However, the device's fragility and limited accuracy made it unsuitable for fieldwork. As an alternative, the project proposes using a photographic-based application capable of extracting color information directly from images of features and findings. To maintain consistency with existing documentation practices, the proposed system employs standardized color palettes based on Faber-Castell Polychromos pencils, which are widely used for their stability and archival quality. Each pencil color can be mapped to an approximate HEX value through existing online conversion tables or custom calibration. Additionally, unique color palettes will be developed for each excavation site, serving as a reference for future work in the same area. The integration of these color

data into GIS and CAD software ensures visual consistency across digital platforms and supports data reuse in accordance with FAIR principles.

### Results

Although still under development, preliminary testing demonstrates that this approach can create a bridge between physical and digital documentation systems. The proposed method enables the consistent use of color references across excavation drawings, descriptions, and digital models. It also facilitates more precise visual analysis in GIS and CAD environments by linking on-site color observations with standardized digital data. Early feedback from field tests suggests that a photographic approach provides greater flexibility and durability compared to the hardware-based color-scanning device.

### Discussion

This project contributes to ongoing discussions about standardization and reproducibility in archaeological documentation. By combining traditional materials with digital methods, it enhances the reliability and longevity of color data while preserving established practices valued by archaeologists. The application of FAIR principles ensures that the resulting color datasets are findable, accessible, interoperable, and reusable, thus improving data management and comparability across excavations. The proposed workflow not only benefits field archaeologists but also supports curators, digital archivists, and researchers seeking to integrate consistent color information into broader archaeological datasets. Future development will include testing the app across multiple sites and refining the color conversion system to improve accuracy and user experience.

## 207. Managing Complexity: A Digital Management System for Experimental Archaeology

*Syed Ghaus Rabbani (Leibniz Zentrum für Archäologie (LEIZA))*

*Ivan Calandra (Leibniz Zentrum für Archäologie (LEIZA))*

Archaeology employs experimentation to understand past human behaviors, technologies, and cultural practices through hands-on reconstruction and testing. Archaeologists generate complex datasets requiring meticulous documentation to ensure scientific validity. Critical gaps exist in documentation and reporting of experiments. There is no agreement on what metadata should be reported and in which form. Paradata—the intellectual processes behind interpretative decisions—are rarely reported, yet it is crucial for understanding experimental reasoning and enabling replication. Sample preparation protocols vary widely between researchers and institutions, while analytical procedures often lack documentation for independent verification. These challenges are compounded by experimental archaeology's interdisciplinary nature drawing on fields like materials science, anthropology, engineering, each with distinct methodological traditions. This presentation introduces a comprehensive, open-source experiment management system developed in the frame of the NFDI4Objects consortium designed to address the fundamental challenges in experimental archaeological research. The experiment management system provides a visual flowchart interface allowing researchers to map experimental procedures intuitively, making complex multi-step processes accessible and reproducible. Key capabilities include seamless integration with lab instruments and electronic lab notebooks, enabling real-time data capture and reducing manual transcription errors. Experiments can be

exported in open formats to ensure compatibility with different publication and archival requirements. Specific experimental data can be extracted separately for targeted analysis.

Recognizing the diverse needs of the experimental archaeology community, the system is designed for maximum accessibility and adaptability. It processes multimedia content including images, videos, dictionaries, taxonomies, and ontologies—essential for capturing the rich, multi-modal nature of experimental data in archaeology. This approach to experiment management aims to enhance reproducibility, share knowledge, standardize methodologies, and advance scientific rigor.

### Technical Architecture

The experiment management system implements a simple architecture optimized for open source contribution. The front end of the application is built entirely in Svelte JS. A JavaScript framework chosen for its minimal runtime overhead, and superior rendering performance. The component-based architecture enables modular development of specialized UI elements including the flowchart canvas, multimedia viewers, and data validation interfaces, while maintaining a consistently responsive experience across desktop, tablet, and mobile form factors.

The middle ware and backend are written in TypeScript which is popular today and works well with JavaScript. This almost unifies everything except the database. It seems like the whole application was written in just one language.

The RESTful API architected around resource-oriented endpoints that serve dual purposes: facilitating internal frontend-backend communication and providing external integration capabilities. API authentication employs JWT (JSON Web Token) standards with refresh token rotation to maintain secure, stateless sessions. The integration framework supports bidirectional data flows with heterogeneous external systems through a plugin architecture that abstracts vendor-specific protocols. Connectors for electronic lab notebooks (ELNs) such as eLABFTW, implement standardized adapters that normalize incoming instrument data—including spectroscopic measurements,

microscopy images, and chromatographic outputs—into a unified internal schema. Outbound API endpoints support programmatic data extraction with filtering, pagination, and field selection capabilities, enabling researchers to integrate experimental data into statistical analysis pipelines, machine learning workflows, or institutional repositories.

The database is a good old relational PostgreSQL, leveraging advanced features including JSONB columns for flexible storage of heterogeneous experimental metadata, full-text search capabilities for rapid paradata retrieval, and row-level security policies to enforce fine-grained access control at the database level. The schema design implements a hybrid normalized-denormalized structure: core experimental entities (projects, workflows, steps, users) follow third normal form to ensure referential integrity, while experimental observations and instrument outputs are stored in semi-structured JSONB format to accommodate the domain's diverse data types without schema migrations. Native support for temporal queries enables complete audit trails of experimental modifications, critical for scientific provenance tracking.

User management implements hierarchical role-based access control (RBAC) with three predefined roles (Administrator, Team Leader, Researcher) and support for custom role definitions. Permissions cascade through organizational units and project hierarchies, with granular controls at the experiment, workflow, and individual step levels. The authorization model distinguishes between ownership, collaboration, and publication permissions, enabling researchers to maintain private working spaces while selectively sharing read-only snapshots or enabling collaborative editing with defined team members.

The flowchart visualization engine employs an open source library to represent experimental workflows, with nodes encapsulating discrete experimental steps and edges representing material flows, temporal dependencies, or conditional branching logic. The rendering layer uses HTML5 Canvas with WebGL acceleration for fluid pan, zoom, and node manipulation. Node templates are extensible, supporting rich metadata capture including protocol references, parameter sets, sample identifiers, timestamps, and

embedded multimedia. Conditional branching allows researchers to model decision trees within experiments, documenting how observations at one step influenced subsequent procedural choices—directly addressing the paradata documentation gap.

Export functionality implements format-specific serialization pipelines: PDF generation produces reports with embedded vector graphics and preserved hyperlinks; JSON exports follow a documented schema specification enabling machine-readable data exchange with preservation repositories; SVG exports of flowchart diagrams maintain editability in vector graphics applications. Each export format preserves complete metadata chains including timestamps, user attribution, and version history to satisfy FAIR data principles.

The publication module implements an immutable snapshot mechanism that creates read-only copies of experimental workflows with assigned DOI-compatible persistent identifier. Versioning support enables researchers to publish iterative refinements while maintaining bidirectional links between versions, documenting methodological evolution over time—a requirement for long-term experimental programs common in archaeological research.

Deployment architecture supports both cloud-native containerized environments (Docker/Kubernetes) and on-premises installations, with configuration management through environment variables and external configuration files.

The system can be hosted both by an institution or run directly on laptops or personal computers.

## 215. A GIS-Enabled Application for Bayesian Optimal Allocation of Effort in Archaeological Surveys

*Edward Banning (University of Toronto)*

*Steven Edwards (Nova Scotia Community College)*

Operations Research during the Second World War pioneered methods for optimally allocating search effort in such applications as detecting U-boats and survivors of downed aircraft. However, these methods have had very little impact in archaeological survey, partly because of archaeologists' perception that they are impractical, difficult to carry out or too mathematically complex. Building on previous experiments with these methods on archaeological surveys in Cyprus and Jordan, we have developed a prototype of a GIS-enabled application that automates the processes involved in optimally distributing surveyors to survey regions in a predictive model, with prior probabilities assigned through elicitation of expert opinion or other methods. Especially where resources are scarce, regions to be surveyed are large, or target sites are difficult to find, we argue that this approach greatly improves the probability of discovering rare or unobtrusive targets. This application will ultimately be one module of a decision-support system that links Bayesian reasoning, expert knowledge, classical sampling, and detection modeling to improve the efficiency, transparency, and replicability of archaeological surveys.

## 248. The CUD of an Archaeologists' Guide to Good Practice: Bridging Innovation and Infrastructure in Digital Stratigraphic Analysis

*Keith May (Historic England)*

*James Taylor (University of York)*

This presentation will reappraise The Archaeologists' Guide to Good Practice – Handbook (AG2GP-Handbook), developed through the AHRC/UKRI-funded project AH/X006735/1. The Handbook responds to questions raised by its predecessor, The Matrix project, concerning the management of heritage data from field to archive - particularly how commercial innovation can connect with academic research needs (May et al. 2023, May & Taylor 2024). It asks: to what extent are post-excavation (PX) practices and documentation as established as on-site recording methods? and addresses the continuing lack of standardised approaches to the analysis and archiving of stratigraphic and phasing data (May et al. 2025).

Developed collaboratively with major UK archaeological contractors and sector bodies including FAME and ClfA, the AG2GP-Handbook provides online tools and guidance for best practice in PX stratigraphic analysis. It contributes to building FAIR (Findable, Accessible, Interoperable, Reusable) digital infrastructures and more coherent data lifecycles for archaeology. The presentation will outline some of the issues in evolving from a national resource to one with global engagement.

Archaeological stratigraphy is inherently spatiotemporal, yet the records we create (of deposits, structures, and truncation events) remain abstractions of a complex 4-dimensional reality. As anthropogenic impacts intensify, archaeology must play a greater role in contextualising human influence across time and space. However, the absence of intra-disciplinary consensus on documenting these impacts, or even consistent definitions of excavation limits ("Boundary A"), constrains comparability and reuse. Establishing shared

frameworks for stratigraphic and chronological recording is essential if archaeological data are to be reproducible, interpretable, and FAIR across projects and geopolitical contexts.

The presentation will also review the development of Phaser, a prototype tool emerging from the AG2GP project that supports and standardises stratigraphic analysis workflows. Together, Phaser and the AG2GP-Handbook exemplify how pragmatic, project-based innovations can evolve into sustainable digital infrastructure. Accessed by users in over eighty countries, the resources now form the basis for proposed ClfA toolkits, CPD courses, and training materials, ensuring that post-excavation skills and data management continue to evolve alongside archaeological practice.

#### References

May, K., Taylor, J.S. and Binding, C. (2023) Stratigraphic Analysis and The Matrix: connecting and reusing digital records and archives of archaeological investigations. *Internet Archaeology* 61. <https://doi.org/10.11141/ia.61.2>

May, K. & Taylor, J.S. (2024) 'Resurrecting, Re-interpreting and Re-Using Stratigraphy. An Afterlife for Archaeological Data.' *Antiquity*. 98(399), 805–820. doi:10.15184/aqy.2024.60.

May, K., Taylor, J. & Aitchison, K. (2025) Bridging the Post-Excavation Gaps: Structured Guidance and Training for Post-Excavation in Archaeology. *Open Archaeology*, 11(1), 20250049. <https://doi.org/10.1515/opar-2025-0049>.

## 350. From Prototype to Standard – Digital Transformation from Innovative Tool to Added Value?

*Stephan Winkler (illisystems)*

*Nathalie Rodriguez (LWL-Archäologie für Westfalen)*

Digital tools in archaeology often emerge from immediate practical needs - as prototypes designed to address specific requirements. Yet once they are successfully implemented, a second, often underestimated phase begins – the transition from prototype to standard. This talk explores this critical moment in the lifecycle of digital solutions: What happens when experimental applications become part of the established infrastructure? Can software truly become a standard - and if so, for how long should it remain one?

The „LWL-Archäologie für Westfalen“ (LWL-AfW) is a state institution in northwestern Germany charged with the documentation, preservation, and research of archaeological heritage. It oversees an area of approximately 21.500 km<sup>2</sup> and was responsible for more than 300 excavations in 2024. For 19 years the LWL-AfW used „Adiuvabit“, a software for excavation documentation. Using data analysis, the presentation illustrates how tools that were once innovative can, over time, reach their limits if they do not grow alongside changing requirements.

Collected data, legal frameworks, and technical capabilities are changing rapidly – often faster than organizations can adapt their structures and processes. A software that provides added value today can turn into an obstacle tomorrow if its functionality is not reviewed within the framework of quality management and continuously evaluated, developed, or strategically replaced.

The qualitative analysis of digital excavation data and their processes of documentation shows that innovation alone is not sufficient; rather, it must be transferred into sustainable structures. Standards therefore need to be continuously redefined through result-based procedures. Digital transformation changes working practices, communication and leadership styles, as well as expectations of quality in archaeology. It requires conscious and reflective



engagement with digital tools as dynamic systems that evolve alongside users, processes, and requirements. Only in this way can short-term innovation develop into long-term infrastructure.

### 381. From 16 to One - The attempt to create a uniform German data model

*Anna Anzenberger (Illisystems)*

*Stephan Winkler (Illisystems)*

The data model of an archaeological database is only as good as its developer's understanding of archaeology. And since there are many different ideas about how archaeology works, there are also many different data models. Each of these is probably appropriate for the developer's specific region, research period or question. However, different data models lead to differently structured data. These different structures can impair comparability.

This presentation illustrates how the Sapikon data model was created. Starting with two local data models from different regions with different historical focuses and under the constraint of standardisation, a data model was developed that can reflect most current ideas about archaeology and excavation methodology. The form of archaeological data changes depending on the excavation technique, the convention for defining features, the inventory standard for finds and many other specifications. The Sapikon data model is designed to process all this heterogeneous data and structure it in a way that makes it as comparable as possible.

Germany's federal system is a good showcase of how different guidelines alter the data to be collected and what a data model that levels these differences might look like.

### 405. RADOGOST archaeological repository: building a FAIR, interoperable archaeology data service

*Arkadiusz Sołtysiak (University of Warsaw)*

*Marcin Maciejewski (Maria Curie-Skłodowska University)*

*Julia Chyla (University of Warsaw)*

*Wojciech Fenrich (ICM UW)*

*Kamil Filipek (Maria Curie-Skłodowska University)*

*Łukasz Dumiszewski (ICM UW)*

*Łukasz Bownik (ICM UW)*

Archaeological research in Poland remains fragmented across various projects, institutions, and media, with limited reuse due to heterogeneous formats, uncertain licensing, and incomplete metadata. We present the design, implementation, and beta evaluation of RADOGOST (Repository of Archaeological Data Organized in Geographic and Object-based Scientific Theme), a new repository for archaeological research data that combines the robustness of general-purpose repository with domain-specific capabilities for spatial data, object-centric description, and multilingual dissemination. The service is architected for FAIR data stewardship, long-term preservation, and cross-repository interoperability, and aims to support both research reuse and public-facing engagement (including creative-industry licensing). We report what has been built, what worked in beta, the challenges we encountered (legal/ethical, technical, organisational), and the specific metrics and policies we use to move from a pilot to sustainable infrastructure.

#### Methods and materials

**Platform & stack.** The service runs on Fairhive (a Dataverse-based distribution), which provides dataset/collection hierarchies, persistent identifiers (DOIs), file-level access controls, versioning, and extensible metadata schemas. Fairhive carries a CoreTrustSeal certificate and inherits the Dataverse

API ecosystem (deposit, search, harvesting). Repository features used and/or configured include:

- PID policy: DOI per dataset; stable, citable landing pages.
- Access modes: open; embargoed; restricted (request-and-grant); private URLs and anonymous private URLs for peer review.
- Licensing: file-level Creative Commons options; deposit agreements clarifying rights and responsibilities.
- Multilinguality: Polish/English interface and records; roadmap for assisted machine translation backed by a discipline glossary.

Archaeology-specific capabilities.

- Geospatial metadata at the dataset level (with bounding boxes and points) and map-based search to discover collections geographically.
- Discipline vocabularies for chronology/culture, object classes, and investigation types (editable, curated lists).
- 3D model preview for mesh-based files to aid rapid appraisal and teaching reuse.
- OCR/HTR services for scanned documentation and field notebooks to support text search and citation.
- Accessibility: conformance with WCAG guidelines.
- Authentication: national SSO (PBI) integration for depositor access and role management.
- Pipelines & tools: connector to Pandora (data exploration/analysis) to lower the barrier to first-pass analytics directly from deposited material.
- Conversational help (beta planned): a repository chatbot (separate tab) operating over vectorised metadata and text (not images), powered by open-source LLMs; designed for low-cost, offline-first operation and to answer “what’s here and where?” style queries. (Not live in production; evaluated separately during beta.)

Interoperability.

- Metadata exchange configured with existing national repositories (harvest/forward to RepOD and institutional Dataverse instances).
- Aggregator integration: ongoing mapping to ARIADNE Portal profiles for cross-European discovery; export/harvest tests are underway.

- Governance & legal. Repository policies address GDPR/RODO, sensitive locations, embargo use, and cultural considerations; deposit and access workflows are documented for auditability.

## Results

Beta status and content. At the close of beta, the service is feature-complete for deposit, discovery, and controlled access. A starter corpus of 19 curated datasets is prepared for go-live, spanning multiple regions (e.g., Poland, Jordan, Egypt, Ukraine, El Salvador), data types (GIS vectors/rasters, tabular registers, excavation documentation, 3D meshes, photographs, reports), and chronological ranges. This diversity was deliberately selected to stress-test geospatial metadata, vocabulary coverage, previewers, and access/licensing combinations.

What worked.

- Geospatial discovery proved immediately useful for non-specialists: locating datasets by area of interest increased trial downloads in user testing.
- File-level licensing and anonymous private URLs simplified journal review and controlled sharing prior to publication.
- Discipline vocabularies accelerated metadata entry and improved result clustering (e.g., by period or material).
- Embargo and restricted access enabled deposit even when parts of a dataset required delayed or mediated release.

Pain points.

- Heterogeneity of legacy metadata required practical compromises (free-text fields to capture nuance alongside controlled lists).
- 3D preview imposes performance constraints for very large meshes; guidance on decimation and packaging is now part of depositor onboarding.
- Rights clarity for mixed-provenance collections required case-by-case support; we added templates for rights statements and third-party acknowledgements.
- Bilingual records: manual curation is still needed for domain terms; the planned glossary-assisted translation will be evaluated post-launch.

Early integrations.

- National exchange with partner repositories is configured; landing-page tests and basic record propagation are successful.
- ARIADNE mapping: field-to-profile alignment is drafted and undergoing content validation on the starter corpus before enabling regular harvest.
- Pandora link-out: live from dataset pages for selected formats to demonstrate “deposit → inspect” without local software.

## Discussion

From innovation to infrastructure. Moving beyond a pilot required decisions in four areas:

1. Policy & governance: clear deposit and access policies, documented review pathways for sensitive data, and explicit responsibilities for curators vs. depositors.
2. Incentives: lightweight onboarding, DOI-first citation guidance, and support for creative-industry reuse (clear CC licensing) to widen impact.
3. Interoperability: committing to cross-repo exchange and ARIADNE mapping from day one to avoid siloed growth.
4. Sustainability: building on a certified, widely adopted platform (Dataverse/Fairshare) with transparent roadmaps and community support, while keeping archaeology-specific extensions modular.

Measuring progress. For the first production year we track: PID coverage (datasets with DOIs), metadata completeness (share of required/optional archaeology fields filled), geospatial coverage (share with mappable extents), licence clarity (file-level licences present), access mode mix (open/embargo/restricted), accessibility checks (WCAG audits), and reuse signals (page views, downloads, cited datasets). These lightweight indicators help steer training and curation effort where they matter most.

Ethics and legal compliance. For GDPR/RODO we apply minimal-data principles, redact personal data in field documents, and mediate precise site coordinates when necessary. For culturally sensitive content we adopt differential access and require context statements.

What’s next? Priorities after launch are: (a) complete ARIADNE ingestion for cross-border discoverability; (b) expand controlled vocabularies with

community review; (c) release depositor templates & guidance (packaging, 3D preparation, rights statements); (d) evaluate the chatbot strictly as a help system over repository text/metadata; and (e) implement a light reuse-tracking protocol to capture citations and derivative works.

## Conclusions

RADOGOST demonstrates how a discipline-specific layer on a robust repository platform can deliver FAIR and interoperable archaeology data services that meet researchers where they are—without sacrificing governance, accessibility, or legal compliance. Our beta shows that geospatial discovery, file-level licensing, and practical access controls are immediate value drivers, while vocabulary curation, bilingual metadata, and rights clarity require continued investment. The talk offers a replicable blueprint—architecture, policies, onboarding materials, and evaluation metrics—that other communities can adopt to grow from innovation to maintained infrastructure.

## References

Wilkinson, M. D., et al. 2016. “The FAIR Guiding Principles for scientific data management and stewardship.” *Scientific Data* 3:160018.

The Dataverse Project. <https://dataverse.org/> (platform background).

ARIADNE Research Infrastructure. <https://ariadne-infrastructure.eu/>

## S44: Data are People: Data Making as Mirror of Past and Present Practice

*Loes Opgenhaffen, University of York / Saxion University of Applied Sciences*  
*Vasiliki Lagari, Belvedere Museum (Vienna) / International Hellenic University*

**Location:** Hörsaal 05

**Session Format:** Standard

Too often we hear at conferences and courses about the production and aggregation of data, but not about what precedes data: the people creating it (after d'Ignazio and Klein 2023, 7). We hear hardly anything about what this data means or about the subjectivity inherent in using tools to create something: the choices we make in the process of first deciding what is important to document (in 3D) and what is *not*, and secondly, the purpose of the visualisation based on predetermined commercial or scientific objectives (e.g. public outreach, academic publication, project documentation, etc.). These decisions determine both the tools and the resolution of the output, as well as the settings (camera, 3D scanner, etc.), all impacting the final visual result. This means that persons are just as involved in the production of 3D visualizations as the devices they use, and they mutually affect and direct each other and the product. We understand this human-machine engagement as *sociality*.

This implies a social environment of data production: several people are involved, and even more people are involved in the consumption of this data. When we look beyond this anthropocentric perspective and extend sociality to the machine's capacity for action, a synergy arises between the operator and the device. This combination invites a continuous dialogue with our device, which informs our decisions. The limitations that our digital tools sometimes impose actually offer opportunities instead, and stimulate our

*creativity* to find new solutions, adapting (i.e. improving) the devices we use, which are often not designed for archaeology.

The documentation of this synergy can be understood as paradata, emphasizing the social and creative dimensions of data-making. Awareness of the social aspects of production promotes creativity, but standardisation in the documentation of heuristic processes can simultaneously constrain it. The documentation of the creative process can be summarised as a pipeline. The pipeline should not be conceived as a rigid, step-by-step manual; rather, its paradata component provides the intellectual context and creative inspiration for engaging with the tools, which we might call the “machine factor.” The amalgamation of the unique character of heritage objects, volatile nature of technology and changing epistemologies means that both experienced practitioners and novices are constantly faced with new challenges, for which paradata can foster adaptive and innovative solutions.

Although such pipelines cannot be replicated exactly, they offer a flexible framework to guide practice. In this way, paradata bridges two dynamic temporalities – the study of the past and contemporary practices – and offers future researchers a reflective lens on our own social, professional and intellectual worlds.

In this session, we invite researchers and practitioners to share their “creative” methodologies for producing 3D data and to explore whether there are opportunities for a standardised way of documenting our data visualisation processes, with an emphasis on the social aspects of the data creation process (Huvila 2025). By comparing technical pipelines and social practices in academic and development-led archaeology and the GLAM sector, this session aims to promote discussion about practitioners' experiences with technologies in order to find common ground at this specific social level of creating 3D visualisations. These sectors should not each reinvent the wheel separately, but share their expertise to improve registration processes while recognising the social nature of the production process of 3D visualisations of heritage. We are certainly not the first to pursue such a goal, but since there is still no form of shared and accepted standardisation (but there is certainly

a need for it) for documenting and sharing practices such as workflows or protocols (Opgenhaffen et al 2021), this goal must continue to be pursued.

Papers may focus on either or both themes, but are not limited to the following topics, however, we advise to include/apply a reflexive approach by considering the social context they work in:

- Synergy between people and digital devices
- The social production of 3D visualizations of archaeological and heritage objects
- Methodologies of making 3D objects
- Documentation schemes for recording paradata

Standardization of recording production/creative processes

#### Suggested reading:

Huvila, Isto, Lisa Andersson, and Olle Sköld, eds. *Perspectives on Paradata: Research and Practice of Documenting Process Knowledge*. Knowledge Management and Organizational Learning, vol. 13. Cham: Springer, 2024. <https://doi.org/10.1007/978-3-031-53946-6>

Ioannides, Marinos, Drew Baker, Athos Agapiou, and Petros Siegkas, eds. *3D Research Challenges in Cultural Heritage V: Paradata, Metadata and Data in Digitisation*. Lecture Notes in Computer Science, vol. 15190. Cham: Springer, 2025. <https://doi.org/10.1007/978-3-031-78590-0>

#### References:

D'Ignazio, Catherine, and Lauren F. Klein. *Data Feminism*. Cambridge, MA: The MIT Press, 2020.

Huvila, Isto, Lisa Andersson, Zanna Friberg, Ying-Hsang Liu, and Olle Sköld. "A Paradata Reference Model." In *Paradata: Documenting Data Creation, Curation and Use*, 180–210. Cambridge: Cambridge University Press, 2025. <https://doi.org/10.1017/9781009366564.008>

Opgenhaffen, Loes, Hayley Mickleburgh, Martina Revello Lami (2021). "Art, Creativity and Automation. From Charters to Shared 3D Visualization Practices." *Open Archaeology* 7(1), 1648-1659. <https://doi.org/10.1515/opar-2020-0162>

**08:30 – 08:50** 365. Two visualizing archaeologists from different sectors and countries, finding one common ground  
*Loes Opgenhaffen (University of York); Vasiliki Vasiliki (Belvedere, Vienna/ International Hellenic University)*

**08:50 – 09:10** 171. When your tools are not designed for your case – HBIM approach in archaeology and 3D visualisation of an ancient city with procedural modelling  
*Anna Kubicka-Sowińska\*; Wojciech Ostrowski\*; Jakub Modrzewski\*; Łukasz Misk (Jagiellonian University)*  
  
\* *Warsaw University of Technology*

**09:10 – 09:30** 297. The many faces behind one excavation record: A methodology to see the people behind the data  
*Alexandra Katevaina (National and Kapodistrian University of Athens/ American School of Classical Studies at Athens)*

**09:30 – 09:45** Discussion

## 171. When your tools are not designed for your case – HBIM approach in archaeology and 3D visualisation of an ancient city with procedural modelling

Anna Kubicka-Sowińska (Warsaw University of Technology)

Wojciech Ostrowski (Warsaw University of Technology)

Jakub Modrzewski (Warsaw University of Technology)

Łukasz Misk (Jagiellonian University)

In recent years, digital technologies have become indispensable in archaeological research, enabling scholars to document, analyse, and reconstruct ancient sites with remarkable precision. However, challenges arise when existing tools are not tailored to the unique requirements of archaeological data and heritage contexts. Standard Building Information Modelling (BIM) software, optimized for new construction and modern materials, struggles to accurately capture the irregular geometries, material degradation, and chronological complexity inherent in heritage sites (Saygi et al., 2013). However, the possibility of incorporating any type of metadata into a three-dimensional structure seems to be highly useful in terms of parametrical analysis and accurate 3D visualisation. Our approach in 3D environment of an archaeological site is to capture archaeological and architectural relicts, perform a 3D point cloud and then, based on an established workflow, create BIM model of architectural relicts with a description of the archaeological context. An inventive methods for generating digital 3D models in BIM software required the use of unconventional modelling pathways and a decision on what content to associate with the architectural structures. The implementation of this method was generated on the data from Nea Paphos Agora, situated in the centre of the ancient city, investigated by the Polish archaeological team over 60 years (Papuci-Władyka, 2020).

Another approach we implemented to bigger scale of 3D modelling, the entire ancient city of Nea Paphos (Cyprus). Procedural modelling is a powerful

computational technique that uses rule-sets, algorithms, and geometric grammars to rapidly generate complex 3D content, drastically reducing the time and resources required for large-scale reconstruction. The benefits of using CGA modelling also presented specific constraints, which we aimed to circumvent by establishing a custom reconstruction workflow for the various building types across the city's different functional periods. The whole process involved different specialists and different ways of thinking about standardised layout influenced by different parameters.

The results of 3D modelling and reconstructions, both procedural and BIM, were implemented into one environment established on Unreal Engine. Our decision about the chosen parameters to describe ancient building geometry, texture etc. are visible for viewers in the open data platform. Our methodology in creating 3D objects is different for each method, however the common idea is to create a process which will be transparent for the documentation's recipient, regardless of their expertise level.

In our paper, we will show how we solved the problem of the unsuitability of the tools used for modelling ancient cities in individual stages.

Papuci-Władyka, Ewdoksia. (2020). Interdisciplinary research of the Jagiellonian University in Nea Paphos UNESCO World Heritage Site (2011-2015) : first results (E. Papuci-Władyka, Ed.). Historia Jagellonica.

Saygi, G., Agugiaro, G., Hamamcıoğlu-Turan, M., & Remondino, F. (2013). Evaluation of GIS and BIM roles for the information management of historical buildings. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2(5/W1). <https://doi.org/10.5194/isprsannals-II-5-W1-283-2013>



## 297. The many faces behind one excavation record: A methodology to see the people behind the data

*Alexandra Katevaini (National and Kapodistrian University of Athens/ American School of Classical Studies at Athens)*

Archaeological sites usually present a single ‘official narrative’ through publications, on-site signage, or conference presentations. These narratives are typically produced by excavation directors and summarize the results of years of collaborative work. However, they represent only the surface layer. Beneath them lie analysis reports, study seasons, final reports, and, at the foundation, excavation records.

Excavation records are tools for archaeologists to study a site. When adapted for public engagement, they can tell the story of the excavation from a first-hand perspective. By showing the movements, decisions, and motivations of field archaeologists, these records allow the public to connect with the material normally reserved for academic study. In essence, they let the trench supervisors tell the story themselves. Interviewing these trench supervisors during excavations is rarely practiced, and in archival projects it is not even possible. What remains to reconstruct their stories are the excavation records, in forms, photographs, free text, sketches, and GIS vector and raster files. No two sets of excavation recordings are ever the same. They vary between supervisors, projects and evolve over time. They are personal both to the individual and to the project (Huvila et al. 2022; Huvila and Sköld 2021; Hodder 1989). The question then arises: how can we use such a case-specific material?

As part of my PhD dissertation, a methodology is established to produce the history of the excavation through the recording of the trench-level records for public engagement activities. The study focuses on three systematic excavations in Greece, using different recording methods: digital born data in forms, and hand-written notes with sketches and cross sections. The records date from the 1930s and 2010s. The methodology establishes a standardized system with tags and indexed entries to document the knowledge process

behind each action in the field. The unit of analysis is the action itself- sometimes recorded, sometimes omitted in the excavation records.

Working with extensive data to recover the voices of trench supervisors has made one thing clear: many people hide behind this material- the recorders, those who influenced them, and myself as the researcher. These human traces bring excavation histories out of academia and into everyday narratives.

This presentation explores paradata that extend beyond the individual researcher. It considers the people behind our data, both real and inferred, and examines how the act of creating these interpretations reveals my own biases as a researcher. The case studies highlight systematic excavation projects shaped by research agendas and team dynamics. Some of these dynamics are visible in the records; others must be inferred from broader knowledge of archaeological practice in Greece. Recognizing both aspects is essential for meaningful engagement with excavation data.

### Bibliography

Hodder, Ian. 1989. “Writing Archaeology: Site Reports in Context.” *Antiquity* 63 (239): 239. <https://doi.org/10.1017/S0003598X00075980>.

Huvila, Isto, Lisa Börjesson, and Olle Sköld. 2022. “Archaeological Information-Making Activities According to Field Reports.” *Library & Information Science Research* 44 (3): 3. <https://doi.org/10.1016/j.lisr.2022.101171>.

Huvila, Isto, and Olle Sköld. 2021. “Choreographies of Making Archaeological Data.” *Open Archaeology* 7 (1): 1. <https://doi.org/10.1515/opar-2020-0212>.

## 365. Two visualizing archaeologists from different sectors and countries, finding one common ground

*Loes Opgenhaffen (University of York)*

*Vasiliki Vasiliki (Belvedere, Vienna/ International Hellenic University)*

### Introduction

In this paper we explore how practitioners design - planned or impromptu - their creative pipelines, under which we understand the ways they approach 3D recording, modelling, and visualization in archaeology, museums, and heritage projects. By comparing these practices across sectors (academic, commercial, and GLAM institutions), we aim to identify similarities or differences that could help in framing a standardized protocol to flexibly and transparently document 3D work. However, we certainly do not intend to impose one way of working, but to create a shared language for describing how we work — one that acknowledges both the technical and the human dimensions of digital heritage. Approaching the human with the machine, we emphasize the socializing ability, or sociality, of digital devices and the production of 3D data as a living, social practice: one that bridges past and present, connects people and technologies, and invites reflection on how our methods shape the knowledge we produce.

### Theoretical context

Similar to analogue photography, digital recording practice is not without bias or individual choice, however, there is a more or less standardized or accepted set of guidelines for creating artefact photos (Garstki 2018). And it is just because of this standardization that the impact the producer of the images has, is overlooked. With digital practices this impact has only increased and there are hardly standardized digital workflows. Let us now shift focus to the paradox that manifests here: the focus to capture technological change in a standard framework. Technological change has been treated as the constant so far, whereas it is the human always creatively and dynamically responding to the changing technology. Instead, our suggestion is to

treat this human creativity and adaptability as the constant, as the basis for a standardized workflow which reflects social dynamics among diverse participants.

### Theory in action

This rather theoretical explanation can be translated into a practical example. We propose that the dialogue between maker and machine within a social context (Bunel 2004), can be systematically recorded by adopting the chaîne opératoire-approach. The chaîne opératoire or operational chain, with its roots in sociology and praxeology, allows recording a given digital process step-by-step, especially when this is combined with the in digital archaeology widely employed reflexive approach (Opgenhaffen 2021). The different events that constitute a chaîne opératoire, such as conceptualization, data production, processing, and curation, are not fixed but fluid and dynamic. Different participants, with their prior technical knowledge and demands and unexpected external factors, are continuously impacting the process and the final image. In this paper, we will present complete diagrams and reveal the hidden social networks; in this abstract, however, we highlight one event in the operational chain: the conceptualization of the 3D image. This event or entire chain is by no means a fixed hierarchy, although the production follows a fixed technical trajectory. The hidden social network behind the production is complex and hard to tangibly picture.

|                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                            |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Practitioner 1: archaeological research                                                                                                                                                                                                                                                                    | Practitioner 2: GLAM                                                                                                                                                                                                                                                                                                       |
| EVENT 1: Conceptualization                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                            |
| Archaeological situation: an archaeological object is deemed important to document.                                                                                                                                                                                                                        | Heritage situations: projects either focus on a specific group of artefacts, or aim to represent different collections hosted in an institution. (Usually, those projects are short term; few institutions have a permanent designated 3D recording team)                                                                  |
| Visualization aim: research questions require a high level of detail. This directs the choice for technology and its settings. The research aim also requires, for example, no high res texture, but a detailed geometry.                                                                                  | Visualization aim: Research / Public outreach / Emphasis on both (e.g. 3d models in museums that focus on research or where the main end audience is the public. The needs can overlap or precede each other. The difficulty lies when the research goals aim for geometry perfection, and often not attentive to texture) |
| Choice for specific technology is determined by the level of technical knowledge of the operator/archaeological visualizer. Here, <b>events 2-4</b> are in mind.                                                                                                                                           | Same as Practitioner 1                                                                                                                                                                                                                                                                                                     |
| The element of time and budget. In the current research project the aim is to develop DIY systems with low-budget and no-budget solutions. In this case, the required texture is harder to get. The machine captures good geometry, but the cameras are not sufficient.                                    | Choice for tech (partially directed by the goal and specialist's demands), highly relying on budget and already acquired equipment. Budget, demands, and skills are the main criteria often is the case that not all of them are met at the same time.                                                                     |
| Specialist and stakeholders interests are impacting the choice for technical settings: high or low resolution for public display required as well. This directs the choice for an online publication platform to be included in the operational trajectory. Here, the <b>event of delivery</b> is in mind. | Same as Practitioner 1                                                                                                                                                                                                                                                                                                     |
| External factors such as dark studio, stable spaces, visitors or employees touching/moving equipment disrupting the data collection process.                                                                                                                                                               | Same as Practitioner 1                                                                                                                                                                                                                                                                                                     |
| Know-how and implementation of international standards and guidelines. Alignment with F.A.I.R. and institutional/internal policy. Project or institutional metadata- and paradata strategies.                                                                                                              | Same as Practitioner 1                                                                                                                                                                                                                                                                                                     |

The other events are always already anticipated upon in setting the production design in the first event, and therefore occurring already in the mind. Most immediately present is the last event of delivery, as this is determined by the goal of the visualization.

EVENT 2: Data collection

EVENT 3: Data processing

EVENT 4: Creation (the actual 3D artefact)

EVENT 5: Delivery

### Preliminary result

In this early event we noticed a similar development: our experience with the digital technology and knowledge of its affordances, were not meeting the expectations of the pottery specialists and art curators at first. This was and has been a reciprocal process where an exchange of knowledge from the different participants was necessary. The artefact specialists in the situation of both practitioners had to express their own assumptions and desires of the end digital result while the digital archaeologist had to explain the affordances of the equipment and the material agency, i.e. the difficulties that material properties impose. The pottery specialists in the case of practitioner 1 adapted selection procedures according to vessel shape (open/ closed/ challenging features), colour hue and size, and lowered expectations in the amount of objects to scan. The curators in the situation of practitioner 2 had to revise their primary selections of objects (different collections) to ones that were less challenging in terms of preservation status, size and texture properties. In this respect, the 3D recording device acted as a mediator between different participants in the production of 3D artefacts.

### Concluding remarks

The next step is to reflect on how our approach connects to the contributed papers in relation to sociality and social context of data making, and paves the way for a protocol to document 3D recording processes (as paradata).

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## S45: Computational Archaeology at Scale: Large Spatial Datasets for Unveiling Cultural Landscapes

*Jonathan Lim, University of Arkansas*

*Carla Klehm, University of Arkansas*

*Jack Berner, Washington University in St Louis*

**Location:** Auditorium Maximum

**Session Format:** Standard

As spatial technologies advance rapidly in sophistication and become more accessible, archaeologists increasingly wield large datasets to answer landscape-scale research questions. Emerging technologies like light detection and ranging (LiDAR), passive and active satellite sensors, unmanned aerial systems-mounted cameras, structure-from-motion (SFM) elevation data, large-scale geophysical survey, and others are broadly known as high density survey and measurement (HDSM) (Opitz and Limp, 2015; Klehm et al., 2019). The data-rich nature of these datasets multiply the options for analysis, often generating unexpected insights and novel research directions.

For example, airborne LiDAR survey, once exclusively the purview of only the most well-funded projects, are now relatively more accessible by mounting them on UAS units (Risbøl and Gustavsen, 2018), enabling feature visualization and heritage management/monitoring over vast swathes of densely vegetated terrain (Frachetti et al., 2024; Vinci et al., 2025). Open science archival practices further improves access to these elevation datasets, enabling large-scale analysis at minimal cost. Satellites now have near-total coverage of much of the world at very high resolution—beyond direct observation of archaeological sites and the environment, it is possible to produce elevation models of the landscape and even small archaeological features (Lim and Linares Matás, 2023). In order to efficiently study these large HDSM datasets, many archaeologists have turned to machine learning (Bellat et al., 2025).

This field has advanced substantially in recent years and has yielded impressive results, although it is often challenging to identify best practices for specific environment types and cultural contexts.

In this session, we invite researchers to showcase how they have used HDSM datasets in innovative ways. By no means a comprehensive list, topics may include or be tangentially related to the following:

- Large UAS or terrestrial LiDAR surveys, and the challenges of storing and processing such data.
- Satellite remote sensing using passive (Visible light or multispectral) or active (e.g., Synthetic aperture radar) sensors, for direct observation or surface reconstruction.
- Historical imagery, especially imagery that inherently involve complex issues (e.g., Keyhole) in their processing and applications
- Low-cost and open methods for visualizing, processing, and archiving HDSM
- Machine learning for automatic classification or computing change in longitudinal datasets
- Landscape-scale geophysical survey, both vehicle-mounted and pedestrian
- Cloud-based processing workflows for HDSM data in a lab or field environment
- Data fusion of different types of spatial data

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|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 08:30 – 08:50 | 23. Unveiling Entangled Landscapes of the Southern Levant: Spatial Archaeometry with Large Spatial Datasets<br><i>Marcio Teixeira-Bastos (University of São Paulo (USP))</i>                                                            |
| 08:50 – 09:10 | 26. Unveiling Cultural Landscapes through Multi-Scalar Non-Invasive Analysis: Community Organization in Late Neolithic Twin-Circle Settlements<br><i>Petra Basar (University of Pittsburgh); Bryan Hanks (University of Pittsburgh)</i> |

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| <b>09:10 –<br/>09:30</b> | 33. Mapping Bronze Age Pastoralist Habitations in the Eurasian Steppe Using Deep Learning on High Resolution Satellite Imagery<br><i>Jack Berner (Washington University in St Louis); Michael Frchetti (Washington University in St Louis); Denis Sharapov (University of Tyumen)</i> |
| <b>09:30 –<br/>09:50</b> | 91. Hydraulic Landscape of the Highlands: Modeling Water Systems in Early Medieval Central Asia<br><i>Mirae Jo (Washington University in St. Louis); Michael Frchetti (Washington University in St. Louis)</i>                                                                        |
| <b>09:50 –<br/>10:10</b> | 138. A Machine Learning Framework for Vectorising Land Use and Cover from Historic Cadastral Map<br><i>William Ward (University of Exeter)</i>                                                                                                                                        |
| <b>10:10 –<br/>10:30</b> | 326. From Nestor's "Wine Magazine" To Pgi Labels: A Terrain-Aware Wine Landscape of Messenia<br><i>Vayia Panagiotidis (University of the Peloponnese); Vasiliki Valantou (University of the Peloponnese)</i>                                                                          |
| <b>10:30 –<br/>11:00</b> | Coffee break                                                                                                                                                                                                                                                                          |
| <b>11:00 –<br/>11:20</b> | 338. Integrating Airborne and UAS LiDAR for Long-Term Monitoring of Cultural Landscapes: A case study from Western Tennessee<br><i>Jonathan Lim (University of Arkansas)</i>                                                                                                          |
| <b>11:20 –<br/>11:40</b> | 363. LiDAR-Based Storytelling using historical landscapes<br><i>Carla Klehm (University of Arkansas); V. Camille Westmont (University of Alabama at Birmingham)</i>                                                                                                                   |

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| <b>11:40 –<br/>12:00</b> | 380. The Enduring Field: Mapping the Long-Term Management and Abandonment of Andean Agriculture with Deep Andes - a Computer-Vision Foundation Model<br><i>James Zimmer-Dauphinee*; Junlin Guo*; Yuankai Huo*; Parker VanValkenburgh (Brown University); Steven Wernke (Vanderbilt); Cody Berkey*; Rachel Clark*; Greta Cullipher*; Luisa Raquel Mejia Aranguren**; Alexis Reátegui Díaz (Brown University); Manuel Mamani Calloapaza (Vanderbilt Spatial Analysis Research Lab); Oluwatamilore Obisesan*; Kevin Jarra**; Grecia Roque**; Anthony Villar (Brown University); Ericka Guerra**; Ella Wright*</i><br><br><i>*Vanderbilt University<br/>** Vanderbilt Spatial Analysis Research Lab</i> |
| <b>12:00 –<br/>12:20</b> | 393. Inundation innovations: comparing datasets for modeling monsoonal floods, natural catastrophes, and long-term settlement reorganization on the Swahili Coast<br><i>Wolfgang Alders (University of Cambridge); Ioana Dumitru (University of Sydney); Elinaza Mjema (University of Dar es Salaam); Jonathan Soon Lim (University of Arkansas); Dylan Davis (Columbia University)</i>                                                                                                                                                                                                                                                                                                             |
| <b>12:20 –<br/>12:40</b> | 413. Toward continental-scale perspectives on human settlement in the Andes through AI-assisted satellite imagery survey<br><i>Steven Wernke (Vanderbilt); Parker VanValkenburgh (Brown University); James Zimmer-Dauphinee*; Yuankai Huo*; Junlin Guo*; Matthew Ballance (Brown University); Jacob Bongers (University of Sydney); Jose Capriles Flores (Pennsylvania State University); Cristian Gonzalez-Rodriguez (University College London);</i>                                                                                                                                                                                                                                              |



*Ericka Guerra Santander (Universidad Nacional de San Agustín); Frances Hayashida (University of New Mexico); Manuel Mamani Calloapaza\*\*; Luisa Raquel Mejía Aranguren\*\*; Gabriela Ore Menéndez (University of Nevada Los Vegas); Jo Osborn (University of Michigan); Giancarlo Marcone (Universidad Técnica del Perú); Pablo Méndez-Quiros (Universidad de Chile); Alexis Reategui Díaz\*\*; Kevin Ricci Jara\*\*; Grecia Roque Ortega\*\*; Jason Toohey (University of Wyoming); Anthony Villar Quintana\*\*; Xiao Wang (Oak Ridge National Laboratory)*

*\* Vanderbilt University*

*\*\* Independent Scholar*

**12.40 – 13:00** 429. Accessible AI for Archaeology: A User-Friendly Workflow for Predictive Site Detection

*Linduo Li (Institut Polytechnique de Paris), Yifan Wu (University College London); Zifeng Wang (Northeastern University); Youngjie Zhuang (Amazon)*

## 23. Unveiling Entangled Landscapes of the Southern Levant: Spatial Archaeometry with Large Spatial Datasets

*Marcio Teixeira-Bastos (University of São Paulo (USP))*

This interdisciplinary approach aims to explore the complex biosociomaterial entanglements, as theorized by Hodder (2012; 2016), that shaped the Roman-Byzantine Middle East (3rd-7th centuries CE), with a particular focus on human-environment interactions, the development of urban and rural landscapes, imperial frontiers (Roman-Byzantine and Sasanian-Persian), and the

connection between economic and religious networks (Leidwanger; Knappe 2018). To address these multifaceted questions comprehensively, the project uses a broad range of computational tools and extensive spatial datasets. Our methodology, based on Spatial Archaeometry (Opitz et al. 2021), combines geolocated archaeological data (such as wine presses, mosaic pavements, churches, and synagogues) with advanced remote sensing techniques, including historical CORONA satellite imagery and commercial platforms (Lawrence et al. 2012; Luo et al. 2018), enabling planetary-scale analysis. High-resolution 3D reality capture is employed to create detailed digital documentation of archaeological sites and immersive 3D landscape models (Ferdani et al., 2020). These datasets form a "Big Data" and "Data Science" environment (Forte; Murteira 2020), allowing the use of GIS and advanced archaeological network analysis to identify patterns in settlement evolution, resource distribution (such as pottery, wine, and olive oil production), and long-term socio-environmental changes across the Levant region, with case studies in Israel (Yavne, Ashdod, Apollonia, Dor, Beth She'an). By integrating micro-scale material analyses (Ceramic Petrography, ED-XRF, and RHX) with macro-scale spatial data (Lichtenberger et al. 2021; Altaweel; Hanson; Squitieri 2021), this approach creates a "high-definition" view of ancient cultural landscapes.

Keywords:

Spatial Archaeometry, Digital Archaeology, Large Spatial Datasets, Cultural Landscapes, Middle East, Roman-Byzantine, GIS, Remote Sensing, Entanglement Theory.

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## 26. Unveiling Cultural Landscapes through Multi-Scalar Non-Invasive Analysis: Community Organization in Late Neolithic Twin-Circle Settlements

*Petra Basar (University of Pittsburgh)*

*Bryan Hanks (University of Pittsburgh)*

### Introduction

This paper presents an overview of new fieldwork designed to investigate Late Neolithic settlement organization through a fully non-invasive and computationally integrated research strategy. Understanding how communities with contrasting economies and lifeways generated long-term cultural diversity requires analytical frameworks that connect everyday practices, spatial organization, and regional trajectories without relying primarily on excavation. Across Neolithic Europe, the proliferation of enclosures and communal monuments from the late 6th millennium BCE signals changing forms of coordination, labor investment, and collective action. These developments raise key questions about how early farming communities structured cooperation, managed resources, and negotiated social equality within increasingly aggregated landscapes.

Our project focuses on the expansion of Vinča-related communities across the Danube interfluvies and tributaries during the late 6th and early 5th millennia BCE, a zone of intense interaction linking Central Europe, the Balkans, and the eastern Carpathian Basin. Within this contact zone, regional traditions such as the Sopot culture emerged through selective integration of architectural, economic, and social practices. The distinctive “twin-circle” settlements of eastern Croatia—paired, non-intersecting enclosures spaced 3–6 km apart—provide an ideal case study for testing how non-invasive datasets can be used to reconstruct settlement structure, inter-site relationships, and regional organization. While variation in size and layout suggests differing levels of communal investment, their chronology, functional integration, and broader role within settlement networks remain unresolved.

We address the following questions through non-invasive and computational analysis:

- Did twin circles function as joint economic units or discrete household clusters?
- Do differences in scale reflect hierarchy or cooperative networks?
- How did environmental factors shape clustering and inter-site connections?

### Methods and Materials

Fieldwork employs a deliberately non-invasive, multi-scalar methodology emphasizing data integration and spatial modelling. Investigations at Vrbica-Drake, Kešinci-Požarlike, and Glomač combine aerial imagery, UAV-based photogrammetry, geophysical prospection, systematic surface survey, and GIS-based landscape analysis. UAV-derived digital elevation models (DEMs) provide high-resolution topographic frameworks within which geophysical and artefact datasets are spatially registered.

Geophysical prospection integrates magnetometry, electromagnetic induction (EMI), and surface magnetic susceptibility (MS) to detect subsurface features such as ditches, pits, hearths, and activity zones. Transect-based surveys establish regional baselines, while multi-channel datasets are processed and visualized as composite layers in QGIS to enhance interpretability. Systematic pedestrian surface collections complement geophysics, with artefact counts and weights interpolated into density surfaces and compared against geophysical anomalies and soil properties. Together, these datasets enable computational assessment of household clustering, activity zoning, and enclosure morphology without excavation.

### Preliminary Results

Integrated analysis of UAV-derived DEMs, MS measurements, and EMI survey data distinguishes natural soil variation from anthropogenic features and clarifies internal settlement organization. At Kešinci-Požarlike, combined datasets reveal central zones likely associated with communal activities, while conductivity mapping at Vrbica-Drake indicates enclosure ditches and

possible settlement expansion. At Glomač, deeper EMI readings identify concentric anomalies and palisade-like features not visible in surface data alone.

Cross-comparison of MS, DEM, and EMI results shows consistent patterning: elevated MS values occur within central zones, with lower values along ditch features. Vrbica-Drake exhibits particularly high MS readings on the central mound with additional peripheral concentrations, while Glomač shows stronger activity signals toward the enclosure margins. At Požarlike, anomalies form a ring around the central area. Collectively, these patterns suggest a single concentric ditch at Glomač and Požarlike and a double-ditch configuration at Vrbica-Drake, each enclosing a central mound.

### Discussion

These results demonstrate the potential of integrated non-invasive and computational approaches to address questions of socio-spatial organization traditionally reliant on excavation. The first analytical stage focuses on household differentiation, activity patterning, and resource management within twin-circle settlements, assessing whether small-scale enclosures were embedded within hierarchical systems or cooperative networks. By situating settlement morphology and internal organization within a GIS-based environmental framework, we evaluate how soil fertility, water access, grazing potential, and raw material availability influenced settlement placement and inter-site relationships.

Planned integration of isotopic data from faunal remains will provide proxies for grazing regimes, foddering strategies, and land-use intensity, complementing spatial modelling and strengthening interpretations of economic integration derived from non-invasive datasets.

### Conclusion and Future Directions

Ongoing research will assess whether neighboring enclosures such as Glomač and Požarlike represent coeval occupation or sequential re-use through minimally invasive validation. Targeted auger probing and limited excavation will ground-truth geophysical interpretations, refine

chronologies, and provide samples for radiocarbon and isotopic analysis while preserving site integrity. These interventions are designed to integrate seamlessly with existing survey datasets rather than replace them. By foregrounding non-invasive fieldwork and computational data integration, this project demonstrates how multi-scalar spatial analysis can illuminate Late Neolithic cooperation, enclosure construction, and regional connectivity. The approach moves beyond documenting the spread of farming to examine how social networks, communal spaces, and regional identities were materially produced, contributing to broader debates on cooperation, leadership, and community formation in prehistoric Europe.

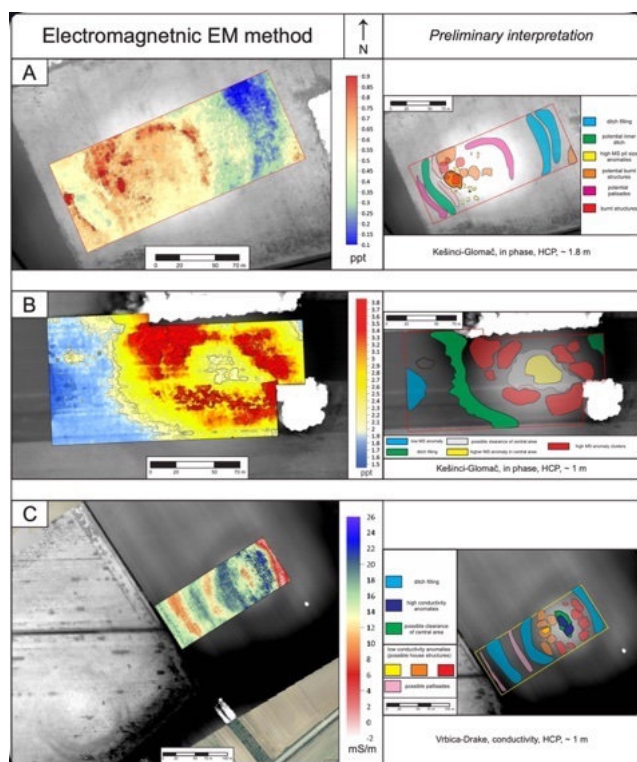


Figure 1. Results of EMI survey (CMD Mini-Explorer) at Kešinci–Glomač (A), Kešinci–Požarike (B), and Vrbica–Drake, NE enclosure (C), with preliminary interpretation of geophysical anomalies.

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## 33. Mapping Bronze Age Pastoralist Habitations in the Eurasian Steppe Using Deep Learning on High Resolution Satellite Imagery

*Jack Berner (Washington University in St Louis)*

*Michael Frachetti (Washington University in St Louis)*

*Denis Sharapov (University of Tyumen)*

The Central Eurasian Steppe (CES) is the largest grassland on Earth. Since the Bronze Age, it has been home to seasonally mobile and low-population-density pastoralist communities that occupied geographically extensive cultural landscapes. In the Late Bronze Age CES, numerous aggregated and fortified

pastoralist communities emerged, such as those of the Sintashta-Petrovka horizon (2000-1700 BCE; Koryakova and Epimakhov 2007). While large fortified settlements from this period are well-documented, the broader regional-scale landscapes surrounding them remain understudied (Hanks and Doonan 2009). This data gap exists partly due to logistical issues; no more than 30 fortified pastoralist communities have been identified in an 80,000 square kilometer expanse of grassland interfluvies, and using traditional field survey to identify small pastoralist hamlets in these sites' hinterlands is a prohibitively time-consuming task (Soldatkin 2020). One promising avenue toward addressing this issue is full-coverage survey using high resolution satellite imagery to map clusters of pastoralist habitation depressions. To this end, we present the early results of a remote survey of ~20,000 square kilometers of high resolution Maxar imagery in the steppes of Northern Kazakhstan, where we use object-based deep learning to identify hundreds of potential Bronze Age habitations in the steppe river valleys surrounding fortified Sintashta-Petrovka sites. We also use a combination of RGB and panchromatic Maxar imagery with 8-band PlanetScope imagery for a brute force survey in three areas deemed likely to contain unfortified Bronze Age settlements. The high-confidence Bronze Age settlements identified by deep learning and brute force survey require in-situ ground truthing, therefore, our approach functions as a self-improving loop in which satellite image analysis informs fieldwork, which in turn provides additional training or validation data for the next batch of remote prospection. In this presentation, we showcase one iteration of our approach; our pre-trained model identified numerous possible habitation depressions in the vicinities of a Sintashta-Petrovka settlement, and when ground-truthed predictions are fed back into the model, we see qualitative improvements. Ultimately, the discovery of these Bronze Age pastoralist hamlets will permit a more robust understanding of the regional-scale settlement dynamics at play as proto-urban pastoralist communities nucleated and denucleated. For example, is it possible to observe an emerging center-hinterland dynamic surrounding fortified sites ca. 2000 BCE? Additionally, to what extent did nucleated pastoralist landscapes persist after fortified sites were abandoned? Answering these

questions will undoubtedly require high-resolution regional scale settlement patterning data that is best obtained through mesoscale remote survey and targeted field testing.

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## 91. Hydraulic Landscape of the Highlands: Modeling Water Systems in Early Medieval Central Asia

*Mirae Jo (Washington University in St. Louis)*

*Michael Frachetti (Washington University in St. Louis)*

How did cities thrive in mountain environments where water was scarce and unpredictable? Water has long been regarded as central to urbanism, yet most discussions focus on lowland river valleys and oases, where irrigation sustained large populations and complex political systems. In contrast, highland regions remain largely overlooked, leaving major gaps in understanding how urbanism emerged in high-altitude mountain environments with limited and seasonal water availability. In this context, this research asks: how do



humans shape natural hydrological systems to facilitate urbanization in extreme environments?

To address this question, the study examines the hydraulic landscape of Tugunbulak (6th–11th c. CE), a medieval nomadic city situated at ~2000 m in the Malguzar Mountains of Uzbekistan. Using recently generated high-resolution drone LiDAR data (spanning 158 ha, 2.5 cm/pixel) (Frchetti et al. 2024; Maksudov et al. 2019), the research applies computational hydrology, geomorphological mapping (Jones et al. 2007), and archaeological interpretation to reveal how natural hydrology, artificial water systems, and urbanism structure one another.

Three analyses derived from LiDAR data are conducted: first, the analysis examines how sink and flow accumulation models can be used to identify traces of artificial water systems; second, least-cost path analysis is modeled to find optimal routes between water sources and urban features on the plateau; third, it documents erosional and depositional features that shaped and were shaped by past hydrological processes to understand landscape dynamics influencing the development of artificial water systems. In doing so, this research demonstrates how large-scale, very high-resolution (VHR) surface models can be leveraged to reconstruct hydrological systems in rugged mountain terrain.

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### 138. A Machine Learning Framework for Vectorising Land Use and Cover from Historic Cadastral Map

*William Ward (University of Exeter)*

Historic maps are a profoundly valuable yet underutilised resource in landscape history, with their full potential locked behind the immense effort required to create spatially-explicit datasets. This research addresses the gap in methodologies for deploying Convolutional Neural Networks (CNNs) on entire map series to develop a practical, efficient framework for comprehensive feature vectorisation despite inter-series survey differences between map sheets.

This project developed and evaluated a machine learning (ML) framework for vectorising cadastral maps, using the 1830s Tithe maps of South West England as a case study. An annotation ontology relying solely on visual information (Petitpierre and Guhenne, 2023) was defined to train two separate U-Net models on PyTorch: one for binary linear boundary detection using an improved architecture (Ran et al. 2022), and another adapted for multi-class land cover area detection and document damage detection. Comparing a purely manual effort to the ML-assisted pipeline demonstrates a hybrid approach is most effective. The linear boundary vectorisation significantly outperformed manual annotation in speed, yet the multi-class land cover area segmentation struggled to achieve clearly defined polygons. However, the document damage class stood out as a helpful tool for highlighting areas of lost information in the final vector dataset.



From this exploration, a Python-based toolkit for digitising Tithe maps of England and Wales was produced with pre-trained model weights and a QGIS-based pipeline for turning raster prediction masks into spatially projected vector data equivalents was designed. For researchers working on different map series, the models can be trained on new data and the toolkit can similarly be used to process predicted masks into vector data.

This research provides a practical, transferable framework for researchers to rapidly digitise land cover and use from similar cadastral map series. By demonstrating a viable ML-assisted pipeline for the most labour-intensive element of linear boundary extraction, this pipeline shows a promising hybrid approach to replace purely manual processing. Additionally, the ability to identify patterns in documents reflecting areas of damage proved as a useful addition to the practice of historic map vectorisation.

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## 326. From Nestor's "Wine Magazine" To Pgi Labels: A Terrain-Aware Wine Landscape of Messenia

*Vayia Panagiotidis (University of the Peloponnese)*

*Vasiliki Valantou (University of the Peloponnese)*

Introduction: This paper reconnects key lines of wine evidence from antiquity to the present within the modern geographic prefecture of Messenia. The region including the Pylos and Kalamata areas. hosts PGI labels of Pylos,

Triphylia and Messenia (ΠΓΕ Πυλία, Τρι-φυλία, Μεσσηνία) where we link wine geography to show how topography. Considering archaeological and historical evidence along with geographic morphology and geographic information system algorithms this project attempts to give the lineage of wine in the region of Messenia. From the Palace of Nestor's "wine magazine", a storage building with pithoi and at least 60 sealings, four bearing the Linear-B wine ideogram, to PRAP's regional syntheses (Hesperia; Sandy Pylos) that chart settlement distributions, corridors, and estate density across Messenia from prehistory to post-classical times the bibliography includes many confirmations and studies of wine production, consumption and trade. In order to achieve an overall review of the scientific documentation an additional heritage thread include archaeobotany studies near Romanou (P.O.T.A.), where Early Helladic II contexts yielded thousands of *Vitis* macro-remains (grape pips/charcoal), strengthening the case for early viticulture/winemaking potential on the Romanou littoral north of Navarino [1].

The study transits to the present with a concise reading of PGI rules and spatial envelopes: PGI Pylos (est. 1989) covers the southwest of Messinia, municipalities including Pylos, Methoni, Koroni, Petalidi, Papaflessas, Aepia, Voufrades, Hiliohoria, with vineyards above 50 m and a white leaning varietal set (e.g., Assyrtiko, Roditis). PGI Messinia likewise requires ≥50 m and features efforts to bottle the local Fileri (a Moschofilero-family clone) alongside international varieties [2]. Local practice is demonstrated for this study via Nestor Winery, a long-standing regional node referencing PGI Pylos/Triphylia/Messenia, to illustrate cooperative-to-private transitions and logistics today. For national scale context, we add one trend datapoint from ELSTAT's vineyard survey, summarizing areas under vines and the share intended for PDO/PGI wines.

Methods and Materials: All mapping uses Greek Grid '87 / EPSG:2100. A light, terrain-aware sketch is presented using a 10–30 m DEM (slope, wetness), indicative stream-crossing penalties, and a least-cost corridor overlay linking palace/estate nodes to modern PGI belts and port logistics around Navarino. A two-panel figure shows:

(i) Pylos/Englianos and Romanou points on shaded relief with indicative terrace belts;

(ii) PGI polygons with example corridors illustrating slope-friendly movement.

Results: Deliverables include an ArcGIS storymap for public exploration, a compact GeoPackage (heritage points, PGI envelopes, corridor sketch), and a concise, reproducible methods note that both explains the cost-surface choices and frames terraces as living heritage, stabilizing vines, soils, and water while sustaining PGI value [3]. Together, these show how archaeological evidence and PGI policy co-inform spatial decisions and offer a scalable template for wine-landscape stewardship in the southwestern Peloponnese.

Discussion: Findings point to a durable alignment between historic wine places, terrace belts, and today's PGI zones. Treating terraces, passes, and fords as living heritage gives heritage managers and growers a shared, practical basis for light-touch conservation and route interpretation, linking quality, access, and care for the land without over-specifying exact lines. In doing so, the study reuses existing digital archives and open datasets (PRAP syntheses, SearchCulture records, Wines of Greece PGI documentation, ELSTAT vineyard statistics) to build a transparent GeoPackage + StoryMap that is FAIR-by-design. Practical obstacles to reuse such as uneven metadata and spatial precision are noted and addressed.

Keywords: Pylos, PGI Πυλῖα, Messinia, Linear-B, archaeobotany, least-cost paths, terraces

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## 338. Integrating Airborne and UAS LiDAR for Long-Term Monitoring of Cultural Landscapes: A case study from Western Tennessee

*Jonathan Lim (University of Arkansas)*

Light detection and Ranging (LiDAR) sensors provide a means to visualize topography, while minimizing or eliminating the presence of vegetation. The high-density nature of this type of data allows for a multitude of different types of analysis across scientific disciplines to be carried out in the service of heritage management and archaeological research (Klehm 2023). In 2024, a unmanned aerial survey was carried out at the Pinson Mounds State Archaeological Park and the nearby Johnston site in Madison County, Tennessee, using remotely-sensed LiDAR data. It is one of the largest UAS LiDAR surveys for heritage purposes, carried out over two days. The Pinson Mounds are one of the largest and most important sites of the Middle Woodland period for the Hopewellian cultures, a time of sophisticated social organization and trade (Henry et al. 2020). The site includes twelve substantial mounds, including five large platform mounds ranging in height from 3m–22 m, and dating from A.D. 1–500

The study focuses on the erosion on the plateau flanks of these two upland sites, where numerous gullies are evidently expanding to threaten archaeological features. In order to define the extent of erosional damage that has occurred over this 12-year period, three airborne LiDAR datasets were analyzed: Two USGS piloted airborne LiDAR surveys from 2012, 2019, and the

NSF SPARC UAS survey in 2024. The research had three main components: first, to identify and quantify the erosional "hot spots" and assess the directionality of the erosion; and second, to use simple linear regression to project future landscape changes, specifically at 5, 10, and 15-year intervals from 2024. Finally, the detailed and dense elevation information afforded by the LiDAR dataset allows geometric characterization of known structures and their extents and aids in the prospection of undocumented features, further contributing to the management and research strategies of the Pinson Mounds complex.

The most compelling finding of this study is that the majority of erosion taking place in this region is occurring within the gullies, which is an argument for taking measures to prevent their formation in the first place. Furthermore, while the predictive models provide a simplistic first-order estimate of future erosion, our study emphasizes the need for continued high-resolution elevation data capture to enable more robust modeling techniques, such as random forest machine learning regression, for long-term monitoring and planning purposes. Another major output of this research was the modernization of geospatial tools developed by Jennifer Cartwright and Timothy Diehl in 2012— using the Pinson Mounds as a testing area, they created a set of hydrological tools to identify areas of geomorphologic instability, such as steep banks, abrupt changes in channel slope, or areas of rough terrain (Cartwright and Diehl 2017). The danger areas identified coincide with the known bank erosion visible from 2012–2024, further highlighting the utility of the LiDAR dataset for monitoring geomorphological change in culturally sensitive landscapes, particularly in areas with thick vegetation cover. The dense nature of the data facilitates a multi-disciplinary approach to heritage management, allowing different types of analysis to be carried out to answer a variety of research questions.

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### 363. LiDAR-Based Storytelling using historical landscapes

*Carla Klehm (University of Arkansas)*

*V. Camille Westmont (University of Alabama at Birmingham)*

This presentation focuses on the use of LiDAR to offer not just unique, but nuanced perspectives to the past. It considers how LiDAR can be used as a storytelling platform, focusing on novel, integrative ways of communicating contentious histories.

LiDAR is increasingly common in archaeology, especially landscape archaeology, for the identification of features, sites, and settlement patterns over vast geographic areas and through dense vegetation. LiDAR aids in the visualization of man-made structures, anthropogenic impacts on the environment, and other various environmental processes, providing insight into both where and how people have lived in the past.

And yet, how LiDAR and the interpretation of LiDAR data can be a theoretical lens to learn something more, and something different about the past is comparatively less developed (Inomata 2024, Klehm and Westmont 2025). Storytelling, while often framed as outreach and an afterthought—to disseminate data to stakeholders and the public—is fundamentally theoretical: No data make sense without an interpretive framework.

As one of a few case study examples, we will engage with the long *durée* of race, inequality, and poverty in Appalachia (Klehm and Westmont 2025). Across the American South, between 1868 and 1928, tens of thousands of African American men, women, and children were arrested on trumped-up charges, convicted in racially biased courts, and sold as enslaved laborers to private businesses, all of which was legal and encouraged under the Southern convict lease system (Westmont and Colclasure 2024). In southern Middle Tennessee, this system was centered around the Lone Rock Stockade, located in the heart of the Grundy Lakes valley. We demonstrate how storytelling with spatial data from Grundy Lakes can capture the relationships between people and geography, relationships that have been folded into, like the hollers themselves, the historical contingencies that have given them form. Storytelling serves as an interpretive mechanism, with spatial data providing perspectives that bring together events more holistically, rather than dealing with them sequentially. All data tell a story; critical engagement with LiDAR help tell that story differently.

Deeper engagement with LiDAR imagery offers an avenue toward more critical histories. It can provide a means to consider stories that have been rendered ungeographic; and landscape storytelling serves as a collective approach that identifies connections throughout time that highlight enduring truths and contradictions represented in the social memory of different communities. We aim to encourage archaeologists to think critically about how they may generate more inclusive and less linear histories in their work that consider commonalities across time and historical events.

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### 380. The Enduring Field: Mapping the Long-Term Management and Abandonment of Andean Agriculture with Deep Andes - a Computer-Vision Foundation Model

*James Zimmer-Dauphinee (Vanderbilt University)*

*Junlin Guo (Vanderbilt University)*

*Yuankai Huo (Vanderbilt University)*

*Parker VanValkenburgh (Brown University)*

*Steven Wernke (Vanderbilt)*

*Cody Berkey (Vanderbilt University)*

*Rachel Clark (Vanderbilt University)*

*Greta Cullipher (Vanderbilt University)*

*Luisa Raquel Mejia Aranguren (Vanderbilt Spatial Analysis Research Lab)*

*Alexis Reátegui Díaz (Brown University)*

*Manuel Mamani Calloapaza (Vanderbilt Spatial Analysis Research Lab)*

*Oluwatamilore Obisesan (Vanderbilt University)*

*Kevin Jarra (Vanderbilt Spatial Analysis Research Lab)*

*Grecia Roque (Vanderbilt Spatial Analysis Research Lab)*

*Anthony Villar (Brown University)*

*Ericka Guerra (Vanderbilt Spatial Analysis Research Lab)*

*Ella Wright (Vanderbilt University)*

Archaeologists, government agencies, and NGOs have spent decades studying how peasant communities build, maintain, and abandon agricultural fields in the Andes (Kendall 2005; Pilares 2021). Such research remains relevant because agriculture carried in lands that have been farmed for many hundreds—and often, thousands—of years continues to be the primary source of sustenance for most rural Andean communities. However, fields—

—particularly, terraced fields—have proven to be difficult to study using archaeological field methods. Pedestrian survey remains the most effective way of developing deep understandings of local patterns of field use and abandonment, in conjunction with archival and ethnographic research. Yet it can be difficult to determine how representative such local datasets are of wider patterns of land use. Because fields are both so widespread and so challenging to date using pedestrian survey and excavation, we still lack systematic understanding of their extent and chronology over wider regions. In the absence of such data, archaeologists have sustained common-sense assumptions that terraces are present virtually everywhere in the Andes (Stanish 1987) and that many terrace systems may have been built under the auspices of expansive polities, including the Wari and Inka empires.

Today, there are extensive areas of abandoned agricultural terracing in the central Andes, and questions about what drove their abandonment have been a recurring theme for archaeologists and other social scientists. How much of their abandonment was driven by Spanish colonialism and its devastating impacts on Indigenous communities; how much by the impacts of climatic factors such as the Little Ice Age; and how much might have been driven by the range of factors influencing rapid urbanization in the late 20th century? To adequately address these questions, we need to examine agricultural transformations not within small regions but across landscapes that capture a great deal of the variability (in rainfall, topography, population, and political economy) that they imply. HDSM data in the form of satellite remote sensing data provides the key to generating this broader perspective, and putting deep local research into the broader archaeological context.

Our research has collected data on the distribution and morphology of Andean agricultural fields using both manual, “brute force” (Casana 2014) and automated survey of high resolution satellite images. The former entails coordinating teams of researchers to manually inspect and record agricultural features at the scale of regional valley systems; the latter has involved using users’ detailed maps to train models that enable detailed field mapping at

much larger scales. Our experience has demonstrated that these approaches each have advantages and disadvantages. AI models are effective for generating higher precision data at much greater scales than is reasonable to generate by hand, while trained archaeologists can (when given sufficient time) outperform AI models at mapping agricultural fields at smaller scales given sufficient time (Zimmer-Dauphinee and Wernke 2024). Currently, the macro-regional field surveys enabled by AI have started to transform our understanding of the distribution and scope of agricultural deintensification, demonstrating variation in local strategies of agricultural management across geographic regions.

This paper builds on our previous work (Zimmer-Dauphinee and Wernke 2024), presenting a new semantic segmentation model that goes beyond merely recording the presence and use status (active or abandoned) of agricultural fields to generate a typology of fields based on their morphology and construction methods. By training the AI to include this typology in its detections, we can begin to develop a richer understanding of whether certain types of fields are being prioritized for maintenance (or alternatively for abandonment) and generate hypotheses about the implications of these patterns for the administrative, ecological, and political management of labor-intensive agricultural resources. Furthermore, we expand the scope of our initial 60,000 square kilometer study area to investigate patterns of abandonment across the entirety of the former Inka empire, an area of approximately two million square kilometers. This expansion in scale will give us a broader perspective of the ways in which decisions to maintain or abandon agricultural resources may have varied across the Andes, either from different ecological or cultural circumstances, or as a result of differential policy and enforcement by Spanish colonial administrators.

To improve the model performance and successfully incorporate the added complexity of typology, we leverage DeepAndes 2.0, our custom computer-vision foundation model, which was trained on multispectral satellite imagery extending over the majority of the former footprint of Tawantinsuyu.

Using this powerful model will improve the AI's accuracy over previous efforts and allow us to provide it with a larger context window, reducing the edge effects of the operation that breaks large satellite imagery into smaller chips for processing. Finally, we compare the capabilities of DeepAndes to the current state of the art computer vision foundation models such as DinoV3 for identifying agricultural fields.

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### 393. Inundation innovations: comparing datasets for modeling monsoonal floods, natural catastrophes, and long-term settlement reorganization on the Swahili Coast

*Wolfgang Alders (University of Cambridge)*

*Ioana Dumitru (University of Sydney)*

*Elinaza Mjema (University of Dar es Salaam)*

*Jonathan Soon Lim (University of Arkansas)*

*Dylan Davis (Columbia University)*

Today, the nation of Tanzania is home to some of the largest coastal populations in eastern Africa, posing unique challenges related to climate-induced sea level rise, environmental catastrophes like tsunamis, and seasonal flooding during monsoons. Archaeological research offers a deep-time perspective for understanding adaptive responses to environmental hazards in this region, but this requires suitable hydrological models related to flood risk. In this paper, we present recent large-scale geospatial data applications aimed at creating cost-effective methods for paleoflood modeling in relation to archaeological settlement patterns.

The study area is an 80 sq. km area where the Pangani River meets the Indian Ocean. We compare LiDAR data captured through drone flights to digital elevation models derived from conventional satellite sources, including SRTM, ALOS, ASTER, Planet, and WorldDEM sensors. Using ArcGIS Pro and HEC-RAS flood modelling tools (Alexopoulos et al. 2025; Mubialiwo et al. 2022), we present evaluations of these different datasets and theorize about their significance within local archaeological contexts. They enable a hydrological approach to examine local scales of effect that floods would have had on landscape suitability, and a deeper understanding of long-term strategies for water management and hazard reduction in coastal environments. Flooding may have not only disrupted settlement patterns but also agricultural

potential, depositing brackish water from the river-ocean interface on fields upstream. Vulnerability would have been shaped by proximity to tidal channels, mangroves, and topography. We discuss flood avoidance, the management of riverine resources, and water-borne transport as factors in long-term settlement trajectories from the 6th century CE onward.

CALOR (Dynamic Coasts and Landscapes of Resilience) is a collaborative, interdisciplinary project investigating how Swahili coastal communities in northern Tanzania adapted to climatic and environmental extremes from the 6th century CE onward. This region has faced recurrent droughts, floods, storm surges, and a devastating tsunami in 1000 CE, alongside profound sociopolitical transformations such as urbanization, Islamization, expanded maritime trade, and colonialism (Mjema 2018; 2022). Focusing on Pangani Bay, the project examines how past societies navigated environmental challenges through settlement reorganization, infrastructural adaptations, and long-distance connections. LiDAR surveys from 2024 were aimed at reconstructing coastal landscapes and assesses resilience strategies by aiming to identifying anthropogenic modifications, such as settlements, infrastructure, and water management features. The project also seeks to model landscape dynamics to understand responses to floods, storm surges, and freshwater challenges. By analyzing settlement patterns, the study intends to map how Swahili communities structured their environments to adapt to climatic stressors. The findings contribute to broader discussions on climate risk management by offering valuable historical insights into coastal adaptation.

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### 413. Toward continental-scale perspectives on human settlement in the Andes through AI-assisted satellite imagery survey

*Steven Wernke (Vanderbilt)*

*Parker VanValkenburgh (Brown University)*

*James Zimmer-Dauphinee (Vanderbilt University)*

*Yuankai Huo (Vanderbilt University)*

*Junlin Guo (Vanderbilt University)*

*Matthew Ballance (Brown University)*

*Jacob Bongers (University of Sydney)*

*Jose Capriles Flores (Pennsylvania State University)*

*Cristian Gonzalez-Rodriguez (University College London)*

*Ericka Guerra Santander (Universidad Nacional de San Agustin)*

*Frances Hayashida (University of New Mexico)*

*Manuel Mamani Calloapaza (Independent Scholar)*

*Luisa Raquel Mejia Aranguren (Independent Scholar)*

*Gabriela Ore Menendez (University of Nevada Los Vegas)*

*Jo Osborn (University of Michigan)*

*Giancarlo Marcone (Universidad Tecnica del Peru)*

*Pablo Mendez-Quiros (Universidad de Chile)*

*Alexis Reategui Diaz (Independent Scholar)*

*Kevin Ricci Jara (Independent Scholar)*

*Grecia Roque Ortega (Independent Scholar)*

*Jason Toohey (University of Wyoming)*

*Anthony Villar Quintana (Independent Scholar)*

*Xiao Wang (Oak Ridge National Laboratory)*

Archaeology has long struggled to integrate data beyond regional scales to enable analyses of large scale phenomena such as continental population distributions, societal responses to climate change, and spatially-contiguous views of whole empires. Patchy coverage of systematically-studied areas are separated by vast uncharted expanses. In many areas, it remains fundamentally uncertain how representative the areas that have been studied may be to the larger whole, or what the often less charismatic, more sparsely populated areas might tell us about it. While household- and other small-scale archaeological research has provided valuable corrections to the field's previous focus on "tombs and temples", it is critical that we continue to think beyond local and even regional scales (Altschul et al. 2017). Doing so is important not just because it allows us to capture variation and better avoid sample biases, but also because past peoples themselves frequently understood and acted in their worlds through large scale networks, including empires, circuits of interregional trade, and long-distance seasonal migration.

This is certainly the case in Andean South America, where by the time of the Spanish invasion in 1532 CE, the Inka state had expanded to encompass large areas of five modern republics, populated by at least 10 million diverse peoples distributed across an equally diverse landscape. Field archaeology has made generations of contributions to our understanding of the Inka realm, but its vastness and diversity far outstrip what archaeologists have been able

to study systematically in situ. We see AI-assisted satellite imagery survey as a complementary data source for affording such continuous continental-scale distributional perspectives. So-called brute force (manual visual survey) methods have proven effective for scaling to interregional scales (Casana 2014, 2020; Ur 2013; Wernke et al. 2024), but AI-assisted approaches promise to enable another magnitude of scalar capability. Vision Transformer foundation models are a key tool for these efforts (Guo et al. 2025; Lu et al. 2025). Here we report on initial findings from our AI-assisted satellite imagery survey project, GeoPACHA-AI. Building on an earlier phase of manual visual review ~180,000 km<sup>2</sup> and ~40,000 archaeological loci (Wernke et al. 2024), GeoPACHA-AI developed a Vision Transformer (ViT) foundation model (DeepAndes-Guo et al. 2025), and fine tuned it with the labeled data from the first phase to produce DeepAndesArch, a model for detecting several classes of archaeological loci. Using an expert-in-the-loop approach, our seven collaborating teams headed by regional experts have produced training data and are reviewing, editing, enriching, and analyzing the millions of loci that DeepAndesArch has detected.

We report on initial findings of GeoPACHA-AI, which was deployed across an area approximately coextensive with the footprint of the Inka Empire, an area of about 2M km<sup>2</sup>. The project has developed both semantic segmentation models for landscape features such as agricultural field and terrace systems and large, dense archaeological sites, as well as an object detection model that draws bounding boxes around discrete features. Here we present the object detection model results for archaeological architectural features (discrete buildings) and animal enclosures (corrals) at pastoralist sites. We present frequencies of each locus type, and model performance diagnostics, including Intersection over Union (IoU) of the locus bounding boxes, Precision, Recall, F1-Scores, and mean Average Precision (mAP).

Second, we will present an initial analysis of the macro-scale distributional patterns of these locus types through measures of spatial dependency. It presents locus hotspots at various spatial scales using Getis-Ord  $G_i^*$ , and

more nuanced distributions using Local Moran's  $I$  to distinguish core settlement areas (high-high zones), buffer zones (low-low zones), high-low (high density isolates), and low-high (voids in dense zones). These results will inform subsequent analysis, and we will present likely pathways forward, such as multiscale geographically weighted regression and point process models.

Third, we present the path forward for data editing, enrichment, and interpretation by the collaborating international teams of regional experts. The AI model focuses on the search function, enabling survey coverage an order of magnitude larger than we could achieve by manual visual survey methods. The federated GeoPACHA-AI framework provides a common data schema for teams to pursue specific research agendas and record relevant variables on the detected loci within defined study areas.

Last, we discuss the implications and potential of this new continental-scale archaeological data overlay for Andean archaeology. We see GeoPACHA-AI as purely additive to field archaeology--as a complement to field archaeological research and heritage management. We will discuss our plans to partner with heritage management entities, as well as local, regional, and national agencies by providing the GeoPACHA-AI dataset as a service.

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## 429. Accessible AI for Archaeology: A User-Friendly Workflow for Predictive Site Detection

*Linduo Li (Institut Polytechnique de Paris)*

*Yifan Wu (University College London)*

*Zifeng Wang (Northeastern University)*

*Youngjie Zhuang (Amazon)*

### Introduction

The application of remote sensing and machine learning is rapidly advancing the field of techno-archaeology, offering powerful tools for discovering potential sites over large areas. However, the steep learning curve for accessing and processing geospatial data with professional tools creates a significant barrier for many archaeological experts (Vats and Mehta 2024). This technical gap limits the ability of researchers without a computational background to fully leverage these technologies. To address this challenge, our goal is to answer the question: How can we make remote sensing analysis accessible for the archaeological community?

This study introduces a Python-based workflow driven by Large Language Models (LLMs) and Reinforcement Learning (RL) to bridge this gap. Our primary goal is to provide an accessible, end-to-end system with a non-coding user interface, allowing archaeologists to conduct large-scale predictive surveys. The user interface is designed as a copilot, where users can employ a combination of natural language and intuitive keyboard-mouse interactions. The LLM interprets these commands to call the appropriate functions for execution and guides users through necessary human-in-the-loop operations. Users start by defining a broad region of interest (ROI) and then narrow it down to high-potential locations, thereby optimizing the strategic planning of field surveys and the deployment of expensive resources like UAV and LiDAR.

### Methods and Materials

The core of our contribution is an open-source workflow that automates data acquisition, model training, and site prediction. Our validation focuses on data from Google Earth Engine, specifically Sentinel-2 for multispectral imagery (vision, vegetation, soil) and the FABDEM dataset for elevation (DEM). The analytical process employs a two-stage detection model trained via a three-stage RL strategy designed to overcome the common challenge of limited labeled data.

The detection models operate at two scales: a coarse-grained model to predict the probability of 1x1 km grid cells containing sites, and a fine-grained model to predict the probability of each pixel being site-related. The training for these models unfolds in three stages:

1. Pre-training with Manual Labels: The models are first pre-trained on a small set of manually labeled data. The reward function is twofold: it positively reinforces the identification of archaeological traces while penalizing the recognition of modern features or natural landforms (e.g., rivers, mountains). Specifically, for the fine-grained model, it also rewards the model for generating clustered high-probability pixels, encouraging the detection of continuous patterns rather than scattered points.

2. Vision-Language Model (VLM) Feedback: To augment the small labeled dataset, we introduce a VLM that provides automated feedback. The VLM compares the model's predicted probability map to a reference image containing human-expert labels and generates a positive or negative feedback signal, rewarding predictions that more closely resemble the ground truth.

3. Human-in-the-Loop Feedback: In the final stage, a very small amount of direct human feedback is used to fine-tune the model. This step sharpens the output, making the distinction between site-related pixels and the background more obvious and reliable.

After that, we apply persistent homology to extract topological features from the fine-grained probability map. This technique helps identify significant geometric patterns and compare them against a library of known sites to assist in historical analysis (Jacobs 2025). Finally, the LLM reads materials from similar known sites to generate an analysis of the newly identified patterns, assisting in the explanation of the new discovery.

## Results

We successfully validated the workflow in the Amazonia region for the detection of pre-Columbian sites. Leveraging the hybrid reinforcement learning approach, the models demonstrated a strong ability to identify relevant features despite the limited initial data. The system effectively produced prioritized heatmaps of 1x1 km grids and, for high-priority areas, delivered detailed, pixel-level probability maps that indicate potential archaeological patterns. The topological analysis further identified patterns within these results that correspond to known types of pre-Columbian earthworks. The workflow and its non-coding user interface will be made available as an open-source package.

## Discussion

This LLM-driven workflow represents a significant step toward making advanced computational tools more accessible to the archaeological community. Its three-stage training mechanism effectively addresses the common challenge of data scarcity in archaeological problems. By streamlining the data handling and model training, it enables researchers to easily interact with remote sensing data to answer their specific research questions. The practical implications are substantial, enabling more efficient planning for fieldwork. By open-sourcing the tool, we provide an adaptable platform that can foster a new level of data-driven inquiry in archaeology.

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## S46: The Human Factor in Archaeological Data Recording

*Silvia Götti, Universität Bern*

*Piotr Wroniecki, Montefortino Prospection & Digitalisation*

**Location:** Hörsaal 05

**Session Format:** Standard

The human factors in archaeological data recording New technologies and digital tools promise precision yet archaeological data are still shaped by human choices and limitations. This session focuses on how factors such as expertise, stress, improvisation, or recording bias influence the creation and use of digital archaeological records. We encourage case studies and reflections that show not only where things go wrong, but also how we can design better practices. What lessons can we draw from common mistakes? How can systems be built to reduce human error without ignoring the creativity and flexibility that fieldwork demands? By comparing experiences, we aim to outline practical guidelines for improving data quality in archaeological recording and processing.

Possible topics for presentations include, but are not limited to:

- sources of recording bias and missed opportunities
- improvisation in the field and its consequences
- reorganizing and migrating “grown” or legacy data systems
- creative adaptation or misuse of digital tools not designed for archaeology
- breaking (and fixing) our digital tools in practice
- strategies for designing data systems that reduce human input errors

This session is aimed at archaeologists, computer scientists, heritage managers, data engineers, archivists and everybody else who has to work with the recording and processing of digital archaeological data. We welcome scientific papers as well as anecdotal story telling.



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|---------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 09:45 – 09:50 | Welcome and Introduction                                                                                                                                                      |
| 09:50 – 10:10 | 146. Past Landscapes of Bias and Those Deceitful Digital Methods<br><i>Grzegorz Kiarszys (The University of Szczecin)</i>                                                     |
| 10:10 – 10:30 | 361. Pretty Maps & Partial Truths. The Human Factor in Geophysical Survey Design and Interpretation<br><i>Piotr Wroniecki (Montefortino Prospection &amp; Digitalisation)</i> |

|               |                                                                                                                                                                                                                                                                          |
|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 10:30 – 11:00 | Coffee break                                                                                                                                                                                                                                                             |
| 11:00 – 11:20 | 266. Chaos and stability, the disruptive element of innovation in an established department<br><i>Esther Schoenenberger (Archaeology and heritage management for the canton of Zurich); Kristin Kruse (Archaeology and heritage management for the canton of Zurich)</i> |
| 11:20 – 11:40 | 399. The African Archaeology Archive Cologne (AAArC) - Digitizing, Archiving and FAIR RDM since 2012<br><i>Eymard Fäder (Universität zu Köln)</i>                                                                                                                        |
| 11:40 – 11:50 | Discussion                                                                                                                                                                                                                                                               |

146. Past Landscapes of Bias and Those Deceitful Digital Methods

Grzegorz Kiarszys (The University of Szczecin)

The belief in the objectivity of archaeological remote sensing techniques remains strong in contemporary archaeological practice. This is particularly evident today, for instance, in the context of large-scale remote sensing data and frequent calls for ‘data-driven’ or empirically based, inductive analysis. Such approaches have fostered the widespread assumption that more data leads to better research and a fuller reconstruction of the past.

The sheer detail and volume of digital data can create a false sense of self-explanation, diverting attention from interpretative and cognitive limitations. This aligns with David Cowley’s observation that “the enthusiasm of some archaeologists leads them to jump directly from an observed distribution of archaeological data to an interpretation, without due consideration

of the influence of data collection strategies and of transformations in the landscape caused by ancient and modern land use" (Cowley 2016: 148).

The abundance of evidence derived from modern remote sensing techniques often encourages a misleading sense of completeness. This illusion may prompt researchers to assume—naively—that all necessary elements for constructing archaeological narratives are contained within the collected data, thereby overlooking the essential role of theory and critical approach.

Contrary to this popular perception, the accumulation of data and the application of advanced digital prospection methods do not inherently signify progress in understanding the past. Archaeological sources remain silent until they are interpreted and narrated. Every archaeological record inherently carries survivorship biases—selectively preserving certain phenomena while omitting others. These biases shape the dataset, determining what is visible to researchers and what remains hidden, and thus require critical scrutiny to uncover the missing elements.

Engaging with archaeological records must therefore extend beyond the observation and description of empirical data. It demands a continuous effort to recognise interpretative gaps, address survivorship biases, and acknowledge the epistemological limits of digital methods.

We train AI models in image recognition to identify even the faintest traces of archaeological sites. Yet, there is little reflection on how to recognise biases within the collected data—or how such biases might be addressed using AI itself. As Jacques Derrida observed, "presence is always haunted by absence." Therefore, what is missing is often as significant, if not more so, than what has survived to the present day.

In this paper, I argue that the most important intellectual task in archaeological research does not concern what has been recorded, nor the relationships identified between the observed phenomena. Rather, it lies in questioning what is missing from the dataset—since these absences often hold the greatest potential to transform our understanding of the data. This shift in perspective may qualitatively alter how we interpret the results produced by remote sensing techniques.

Although certain aspects related to fieldwork and data collection will be discussed, the primary focus of this paper is on how archaeologists analyse, interpret, and conceptualise the role of archaeological remote sensing.

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## 266. Chaos and stability, the disruptive element of innovation in an established department

*Esther Schoenenberger (Archaeology and heritage management for the canton of Zurich)*

*Kristin Kruse (Archaeology and heritage management for the canton of Zurich)*

Our archaeological institution has been established in 1958. Since 1989 we have been following a universal guideline which commits us to uniform data collection and data quality. Conservative forces are delighted with this stable state, which has enabled us to collect data continuously in a uniform database for 36 years. Apart from the usual human factor, which doesn't happily deal with standardised data, we encounter another problem. No institution is immune to young "wild ones" who, as soon as they start their career, begin to pull at the threads of the established structure. "We absolutely need to use digital photography! Couldn't we document this hypocaust using a 3D-scan? It would be much faster if we simply recorded the data directly in GIS and omitted the field drawing!" These disruptive minds try out new technologies, the use of which -in time- leads to real innovation. But are the disjointed data piles left behind the price of progress? Or can we anticipate and factor in the effort to prohibit this outcome beforehand? Using real life anecdotes, we will show where we found the traps of unmitigated data chaos

to lie. Perhaps together, we can derive a recipe for future innovative projects!

### 361. Pretty Maps & Partial Truths. The Human Factor in Geophysical Survey Design and Interpretation

*Piotr Wroniecki (Montefortino Prospection & Digitalisation)*

Geophysical prospection is often thought of as an objective, high-resolution way to help archaeologists make decisions. In reality, every magnetic, GPR, or other dataset is the result of human decisions about how to frame the problem, which methods to use, how to collect the data, how to adjust the parameters, how to deal with noise, and how to show the results. This paper analyzes how these human decisions generate bias in archaeological methodology.

It talks about five important steps in the process of forming bias: 1) commissioning and expectations; when tenders, research agendas, or heritage regulations set what "should" be visible; 2) survey design, which includes the extent, sampling density, line orientation, and method selection; 3) data acquisition in the field; 4) processing, where choices about parameters, filtering, and cosmetic cleaning make the data easier to read while getting rid of uncertainty; and 5) finally last but not least, interpretation and cartographic presentation through vectorization and labeling.

The discussion is based on a few case studies that show the most common places where bias can enter into the workflow, from taking measurements in the field to making the final map plots. These examples will demonstrate how practical limitations, anticipations, and individual preferences affect the visibility and usefulness in archaeological research..

The paper contends that these human factors should be acknowledged and recorded instead of being obscured. Geophysical prospection ought to be regarded as a transparent decision-making process rather than a black box.

### 399. The African Archaeology Archive Cologne (AAArC) - Digitizing, Archiving and FAIR RDM since 2012

*Eymard Fäder (Universität zu Köln)*

With digital data hosted by platforms of the iDAI.world (<https://idai.world/>) at the German Archaeological Institute (DAI), for over a decade the AAArC underwent a succession of development phases, challenged by the ongoing dynamics of digital progress.

Starting in 2012, the initial task was to digitize, archive and make available the large corpus of documentation from almost 30 years of African research conducted at the Africa Research Centre (Forschungsstelle Afrika) of the University of Cologne (UoC). Therein included were long-term research units such as BOS (Besiedlungsgeschichte der Ostsahara), SFB 389 ACACIA, The Rock Paintings of the Upper Brandberg as well as a variety of shorter projects. After a brief hiatus, in 2019 AAArC, collaborating with the Data Center for the Humanities at the UoC embraced the task of providing RDM support for the SPP2134 Entangled Africa, with this project still ongoing.

In 2012, the principal focus was to digitize and archive visual research documentation from photographs, pictures and drawings accumulated at the research centre, completed by grey literature generated during the research. These were made accessible mainly through iDAI.objects (<https://arachne.dainst.org/>), the object database at the DAI and the LOD connected platforms iDAI.gazetteer (<https://gazetteer.dainst.org/app/#!/home>) and iDAI.bibliography (<https://ze-non.dainst.org/>). In addition, databases and a collection of documentary movies were archived with the help of IANUS (<https://ianus-fdz.de/>)

To implement this endeavour, a unified data model had to be designed that on the one hand accommodated the diversity of documentation processes used in past research and on the other hand conformed to the digital representation standards at the iDAI.world.

From 2019 on, the eleven interdisciplinary research projects of SPP2143 (<https://www.dainst.blog/entangled-africa/en/home/>) required more specialized platforms than available within the iDAI.world. Following FAIR standards and required LOD connectivity, representation platforms for paleobotanical, dendrochronological, archaeolinguistic and archaeometric data can currently only be represented within platforms not organically connected. After an unsuccessful attempt to develop an integrated explorer, we shifted our focus to the representation through ARIADNE.RI (<https://www.ariadne-research-infrastructure.eu/>) which offers an integrated explorer that makes data findable in associated external systems with the help of a specifically designed data and ingestion protocol. In addition, AAARc contributed a reference framework by expanding legacy data curation beyond research generated in Cologne and added further archaeological reference to the iDAI.world, this time including iDAI.chronontology (<https://chronontology.dainst.org/>).

Across the five funding phases and thirteen years of activities summarized above, the workload encompassed data curation, design of data models and ingestion protocols, transformation of digital data and standard migration, coding ingestion scripts and documenting processes for sustainability. Apart from cooperating with the DAI RDM department, AAARc staff contributed along the way in continuous refinement of the data models adapted during this time period.

From the onset, digital RDM was not yet a firmly established field and the numerous team members therefore required substantial self-training and external support and training, but also paid the price with mistakes and inconsistencies at every conceivable level during the process.

While digital RDM appears to be a very well established discipline these days, this can only be claimed for the actual online representation platforms and associated digital archives. Funding for RDM tasks is not universally established, nor are there universally implemented data models, this in spite of the availability of e.g. CIDOC CRM. The huge diversity of available digital platforms does not necessarily contribute to implementing LOD principles, nor to established international exchange standards. Furthermore, the awareness for RDM requirements is not universally established among scholars of archaeology, nor the necessities of specialized staff to fulfill such duties. With AAARc, we aim at contributing to CARE awareness in the field of African Archaeology and with this paper, to share our experience in providing sustainable RDM.

Lukas Lammers / Eva Reinke / Eymard Fäder, Archäologisches Forschungsdatenmanagement in der Praxis: Das Projekt FAIR.rdm im SPP2143 „Entangled Africa“, Archäologische Informationen 45, 2022, <https://doi.org/10.11588/ai.2022.1.95251>

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## S50: Heritage under Bombs – Mitigating Destruction in Rapidly Evolving World

*Nazarij Buławka, Non-Invasive and Digital Archeology Laboratory (PANiC),  
Faculty of Archaeology, University of Warsaw*

*Oleksandra Ivanova, National University of Kyiv-Mohyla Academy  
Huyam Khalid Mohammed Madani, Cardinal Stefan Wyszyński University in  
Warsaw*

*Mariia Lobanova, Odesa Archaeological Museum of the NAS of Ukraine*

**Location:** Hörsaal 05

**Session Format:** Other

*The session will consist of 20-minute presentations, followed by an extended discussion block at the end.*

Tangible and intangible cultural heritage shape people's sense of identity and their sense of belonging. Heritage is particularly vulnerable during periods of political instability. It can become a silent victim of war through destruction, use in military activities, looting and cultural appropriation, can be politically abused, or be used as a tool to whitewash war crimes. Heritage destruction can be accidental or a deliberate, systemic tool of 'cultural genocide', which aims to erase the memory of individuals and evidence of past communities' existence and culture. Whereas, looted artefacts appear on the black market and are used to purchase weapons, thereby exacerbating further violence (Hanson, 2011).

The situation of heritage is extremely threatened because of the ongoing conflicts and wars around the globe, and the United States' plan of withdrawal from UNESCO. During 2023, we witnessed a third year of the full-scale Russian invasion of Ukraine, continued destruction of Gaza, the war in Sudan, Tigray (Ethiopia), the Democratic Republic of the Congo, India-Pakistan, and Cambodia–Thailand border conflicts, and many more.

During the ongoing war Ukraine's heritage is being constantly destroyed by Russia and artefacts looted. At the same time, such cases as rebuilding of Tauric Chersonesos in occupied Crimea, condemned by UNESCO committee, is an example of cultural appropriation and political abuse of heritage (Mick 2024; Munawar and Symonds 2024; Shydlovskiy et al 2023). Such a violent process is not unique; the situation in Ukraine has received widespread media coverage. In many areas affected by war and political instability, heritage protection is often inadequate and can undergo a similar process. However, information about such situations rarely reaches outside audiences. For example, scholars working in the Tigray region (Ethiopia) report that many museums were looted, and that heritage professionals face particular challenges due to the presence of explosives at destroyed sites.

Since April 2023, Sudan has been experiencing a widespread armed conflict, resulting in a severe humanitarian crisis and the deterioration of security across various regions. This conflict has had devastating effects on cultural heritage, with significant archaeological sites and several museums being affected. Preliminary reports indicate that the damage to archaeological sites may be linked to large-scale population displacement, which led to the use of some sites for housing and agriculture in the absence of adequate protection. More than nine museums across Sudan have also been affected, notably the Sudan National Museum, which was used as a military base, resulting in direct damage from military operations and the looting of its collections. The National Ethnographic Museum, which was completely destroyed by fires caused during direct confrontations. Heritage workers have not yet been able to access museums in the Darfur region to assess the extent of the damage. This situation poses a threat not only to Sudanese cultural heritage but also to the heritage of humanity and calls for urgent action by local and international authorities to safeguard these historical assets from further destruction.

Digitization is emerging as one of the most effective tools for safeguarding heritage in conflict zones, enabling the creation of detailed, shareable, and enduring records of at-risk sites and artefacts. As shown by Radchenko and Hadick (2024) in the Ukrainian context, preserving cultural heritage through

digital means is an interdisciplinary challenge, requiring not only technology and equipment but also trained specialists, sustainable funding, and sufficient time for data collection, processing, and dissemination. In Ukraine, where ongoing hostilities continue to endanger heritage and reduce the number of professionals able to respond, digitization has become both an urgent priority and a logistical challenge. This experience demonstrates that digital preservation efforts in war zones must be internationally supported, well-resourced, and embedded within broader strategies for heritage protection.

During the last CAA meeting in Athens, we discussed the situation of heritage in Sudan, Ukraine, Ethiopia, Syria, Egypt, Armenia, and Azerbaijan. One of the key conclusions of the session was that the CAA must prioritise sessions focused on heritage protection, as this could help develop and introduce new methods and procedures in war zones. A plan for creating a Heritage Under Bombs special interest group was proposed. This meeting will continue to discuss the importance of developing digital methods to document heritage before it is lost.

The session aims to bring together researchers from areas affected by conflict and war, who are deeply concerned about the future of heritage, as well as specialists in digital methods. The session welcomes papers devoted to monitoring archaeological heritage in conflict zones, focused on:

- Inventories, databases for heritage preservation, and Linked Open Data.
- Monitoring: remote sensing (from satellite imagery to Unmanned Aerial Vehicles (UAV)) and citizen science;
- Digital twins: photogrammetry and laser scanning;
- Reports of heritage destruction;
- Heritage protection initiatives.

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| 11:00 – 11:20 | 427. From Documentation to Digital Narratives: Transforming the Odesa Archaeological Museum<br><i>Mariia Lobanova (Odesa Archaeological Museum of the NAS of Ukraine); Oksana Hrytsiuta (Odesa Archaeological Museum of the NAS of Ukraine)</i> |
| 11:20 – 11:40 | 69. Ukrainian Battlespace Management System “Delta”: Important Tool for Cultural Heritage Protection during High-Intensity Warfare<br><i>Denys Grechko (Armed Forces of Ukraine)</i>                                                            |
| 11:40 – 12:00 | 318. Digital Preservation as Mitigation: Photogrammetric Documentation                                                                                                                                                                          |



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| <i>Kseniia Lishchyna (The Odesa I.I.Mechnykov National University)</i> |                                                                                                                                                                                                                                                                                 |
| <b>12:00 – 12:20</b>                                                   | 111. Photogrammetry as a tool for preserving cultural heritage: the example of artifacts from the medieval steppes of Ukraine<br><i>Yaroslav Chentsov (Odesa National Scientific Library)</i>                                                                                   |
| <b>12:20 – 12:40</b>                                                   | 355. From ramparts to trenches. Digital documentation of belligerent landscapes in wartime Ukraine (case study of Bilhorod-Kyivskyi hillfort)<br><i>Oleksandra Ivanova (National university "Kyiv-Mohyla academy"); Ivan Zotsenko (Institute of Archaeology NAS of Ukraine)</i> |
| <b>12:40 – 13:00</b>                                                   | 36. Safeguarding Archaeological Collections at the Musée d'Archéologie Nationale: Foundations and Futures of Data Modelling for Heritage at Risk<br><i>Kai Chun Lennox Yeung (University of Bologna)</i>                                                                        |
| <b>13:00 – 14:00</b>                                                   | Lunch break                                                                                                                                                                                                                                                                     |
| <b>14:00 – 14:20</b>                                                   | 18. Kamyana Mohyla: The Story of the Rock Art Site, its Digital Study, and Outrageous Looting under Russian occupation<br><i>Simon Radchenko (University of Stavanger)</i>                                                                                                      |
| <b>14:20 – 14:40</b>                                                   | 305. The fate of the Neolithic Mariupol cemetery: evidence of the crimes of the Russian occupiers)<br><i>Nataliia Mykhailova (National Academy of Sciences of Ukraine)</i>                                                                                                      |

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| <b>14:40 – 15:00</b> | 37. Translating Heritage Under Bombs: The IOSPE Ukrainian Version as a Case of International Collaboration, Terminological Innovation, and Decolonisation<br><i>Olena Shevchenko (King's College London)</i> |
| <b>15:00 – 16:00</b> | Discussion                                                                                                                                                                                                   |

## 18. Kamyana Mohyla: The Story of the Rock Art Site, its Digital Study, and Outrageous Looting under Russian occupation

*Simon Radchenko (University of Stavanger)*

The rock art site of Kamyana Mohyla (Yyun'-Tash) in the Ukrainian part of the Eurasian Steppe belt is known for its unique assemblages since the late 19th century. Besides being a unique geological formation and a significant landmark, it is a distinct snapshot of numerous historical, cultural, and artistic events that occurred here from the Early Holocene to late Modernity. With this recognition, the site was entered on the tentative UNESCO World Heritage list in 2006 and has been protected as a National Historical and Archaeological Preserve since 2008.

Research on the site started from the late nineteenth century, and continued throughout Soviet history as several intense investigation episodes. Some, like the campaign of 1947, were primarily focused on the archaeology of the region, some (in 1951–1956) were rescue-oriented and aimed at investigating the site before the construction of the water reservoir on the Molochna River, and others, like that of 1973–1974, were focused on the rock art studies. The first complex effort, which also included digital recording of the site, is related to the international projects launched here in 2010. They included an engraved effort on photogrammetric study, contextualization, attribution, and interpretation of rock art artifacts here (Radchenko 2023).

During the spring of 2022, Kamyana Mohyla was rapidly occupied by the advancing Russian forces, which marked an abrupt shift in the contextualization actions on the site and the narrative regarding its possible future. The territory was marked by military presence, illicitly transferred artifacts, and all preservation efforts were put on hold.

Therefore, the digital record formed during 2010–2021 is the cast of the last time that the site was relatively integral. Today, this cast serves as a data source for all open-source intelligence efforts regarding looting, appropriation, illicit activities on the site, and other cultural heritage crimes on Yyun' Tash. By referring to it and exploring Russian media sources, we can determine what was stolen, when, and where. Furthermore, Russian legalization efforts provide a complete picture of how the illicit transfer of artifacts from the site was initiated by the top political establishment in Russia and implemented by local authorities. Of the 1100 artifacts reportedly looted from the site, we have records of almost 230. Up to 60 can be recognized through media sources, and nearly 30 can be clearly identified and recontextualized in their archaeological context.

This paper summarizes available information on the illegal actions taken by Russians regarding the rock art site of Yyun' Tash – from the story of its occupation through the reflection on what has actually been looted and how this was performed, to how we investigate that, which tools we use, and what we learn from it. Besides the reflection on the OSINT and digitization methods and their emergent effect, I will focus on the humanitarian interpretation of these processes with the more detailed consideration of what did digitization brought to the site, how did it change its current state and future perspectives, and how we can interpret the information on the tangible and intangible data that come from the occupation forces and collaborators on the site. To do that, I also explore the initial factors that compelled digitization efforts onsite, demonstrating that the most valuable data were not intended to be, and highlighting the challenges that strategic planning of archaeological preservation faces at frontier locations, such as the Ukrainian Steppe.

My claim is that while the efficiency of digitization efforts for cultural heritage crimes investigation is obvious, preparing for the war, occupation, and OSINT analysis is a strategic challenge that is harder to cope with without previous experience. That being said, the expertise Ukraine unfortunately has now is essential in heritage preservation efforts in the 21st century. Moreover, digital data alone is insufficient for a detailed understanding of the processes at the cultural heritage site under occupation. Context is as crucial as digital recording, highlighting the need for interdisciplinary expertise in analyzing the heritage site in the occupied territory (Radchenko & Hadick 2024). Last but not least, I will draw a connection between the looting of Kamyana Mohyla and wider Russian politics toward the “liberated” lands, emphasizing the general attitude towards cultural heritage there and narratives that heritage preservation is wrapped into (Ivanysko S., G. Kazakevych & P. Shydlovskyi 2024). With this, the talk opens space for reflection on the colonization and cultural genocide policies that are practiced by Russian occupational forces regularly, and extend from the war crimes to the interpretation of prehistoric sites. I will argue that institutionalized looting forms a basis for the “empty land” narrative that the Russian empire uses to justify its military interventions, and that this is precisely what happened, happens, and will happen in Ukraine.

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### 36. Safeguarding Archaeological Collections at the Musée d'Archéologie Nationale: Foundations and Futures of Data Modelling for Heritage at Risk

Kai Chun Lennox Yeung (University of Bologna)

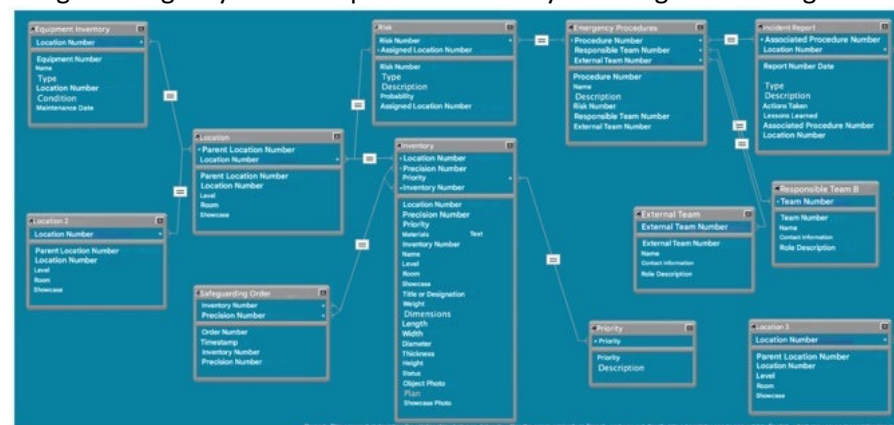
This paper presents a case study conducted at the Musée d'Archéologie Nationale (National Archaeology Museum, or MAN) in Saint-Germain-en-Laye, France, to develop a comprehensive database app to safeguard its archaeological collections. It is part of the wider plan to implement Disaster Risk Management (DRM) strategies for cultural heritage institutions, emphasising the importance of preparedness in an era marked by an increase in frequency and intensity of natural and anthropogenic disasters worldwide. This study employs guidelines and methods published from international cultural organisations, such as the United Nations Educational, Scientific, and Cultural Organisation (UNESCO) and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) to develop and establish strategies for the MAN's DRM.

Research by ICCROM has shown that numerous museums worldwide continue to lack adequate DRM, due to the lack of budget, personnel, space, or knowledge in this crucial field. For the same reasons, the MAN also lacked a comprehensive DRM strategy. Thus, this study first determined the preeminent risk most damaging to the museum, whereby field research and government reports identify fire as the primary threat to MAN's collections. Then, it is determined that an evacuation-based approach is most practical to safeguard the archaeological objects, due to the museum's predominantly wooden interior. To ensure an effective evacuation, a database was created to store all data relevant to the evacuation, the first of its kind for the museum.

The diverse data collected can be incorporated into a multi-faceted custom app in FileMaker, a cross-platform database software that allows users to create apps for managing, organising, and sharing data. In creating an app with an ontological model defining the relationship between datasets, the

different targeted data layouts can support different phases of the DRM cycle, which outline the steps to take before, during, and after disasters. Before disasters, the model enables strategic planning via integrating object information, spatial data, as well as emergency response plans, relevant contacts, and assessment reports. During disasters, a switch in layout gives quick access to the most important information, such as evacuation order and procedures, contacts of relevant personnel, and spaces to record the process. After disasters, the information recorded during evacuation aid recovery and evaluation, allowing for critical analysis and continuous improvement of risk management planning.

The multi-faceted app creates a strong framework that integrates diverse datasets, improving the MAN's risk management planning to safeguard its archaeological collections throughout all phases of the DRM cycle. The low adoption threshold of this app can serve as a basis for other museums' emergency planning, which can also be adjusted and modified depending on the needs and methods of different museums, making it an adaptable and flexible tool. Continuous development of the app will allow archaeological museums to become disaster resilient in face of challenging risks, contributing to the global urgency to better protect humanity's heritage in the long term.



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### 37. Translating Heritage Under Bombs: The IOSPE Ukrainian Version as a Case of International Collaboration, Terminological Innovation, and Decolonisation

*Olena Shevchenko (King's College London)*

The IOSPE project (Inscriptions of the Northern Black Sea – new IOSPE) is an open-access digital corpus of Greek and Latin inscriptions from the Northern Black Sea region. Since 2023, work has been underway on the first complete Ukrainian-language version of IOSPE, developed in collaboration with King's College London (Department of Classics) and the Odesa Archaeological Museum of the National Academy of Sciences of Ukraine, which preserves one of the largest collections of ancient graffiti from this region. This international collaboration has taken place under conditions of active warfare, when both the physical preservation of cultural heritage and the stability of scholarly infrastructure were under severe threat. In the context of air-raid alerts, evacuations, and restricted access to museum collections, digital epigraphy and international cooperation became key instruments for documenting and safeguarding the material.

Translation and encoding were carried out directly within the IOSPE digital infrastructure, using EpiDoc XML (a TEI-compliant standard) and the Oxygen XML Editor for text creation, validation, and version control. While this work, a systemic problem became evident: Ukrainian academic language lacks a standardized corpus of specialised epigraphic, palaeographic, and

philological terminology. For decades, research in this field relied primarily on Russian scholarly vocabulary, resulting in terminological dependency and inconsistency.

To address this gap, the project developed a trilingual Ukrainian–Russian–English glossary of epigraphic terminology, created in parallel with the IOSPE translations. Terminological entries were encoded in accordance with EpiDoc and TEI guidelines, with a semantic structure informed by ISO terminology principles and SKOS-based controlled vocabularies. The resulting terminology is preserved both within IOSPE metadata and as a stand-alone, reusable lexicographic resource, intended for broader scholarly and educational use. The paper discusses: (1) the methodological challenges of digital heritage work under wartime conditions; (2) the role of international institutional partnerships in sustaining epigraphic research; and (3) the formation of a Ukrainian epigraphic lexicon as a tool of scholarly resilience and linguistic decolonisation. This case study demonstrates how digital infrastructures can simultaneously protect cultural heritage, standardise academic language, and reinforce cultural sovereignty in times of crisis.

### 69. Ukrainian Battlespace Management System "Delta": Important Tool for Cultural Heritage Protection during High-Intensity Warfare

*Denys Grechko (Armed Forces of Ukraine)*

Cultural heritage is the basis of the Ukrainian national identity, which Russia is attempting to systematically and deliberately destroy. After Russia launched its full-scale invasion of Ukraine, there was a clear international recognition of the importance of protecting this heritage.

Civil-military cooperation of the Armed Forces of Ukraine (hereinafter – CIMIC AFU) ensures effective interaction between military structures, authorities and the civilian population. One of the interdepartmental tasks of CIMIC AFU is to protect cultural heritage in areas of operation (combat

operations) with the aim of ensuring compliance with the principles and norms of international humanitarian law.

The participation of the Armed Forces of Ukraine and other components of Ukraine's defence forces in the protection of cultural heritage consists of preventing the destruction or damage of cultural heritage sites and cultural values. This goal is achieved by identifying their location in advance.

The preparation of digital maps is important for ensuring the identification of cultural property during armed conflicts. The most effective practice has been to enter information about cultural heritage sites into the national military situational awareness system DELTA, which is used by Ukraine's security and defense forces for planning and conducting military operations.

DELTA is a situational awareness and battlefield management system developed by the Ukrainian military services for use in repelling Russian armed aggression (Bondar 2024). It is a cloud-based, large-scale Ukrainian military integration platform designed and developed by the Armed Forces for operational use. It stands out for its capacity to generate comprehensive situational awareness tools, including a digital mapping environment that supports both manual data entry and seamless integration with multiple sources such as sensors, trackers, radars, and satellite imagery providers. Through these integrations, users can monitor friendly troop positions, detect enemy movements, and, importantly, visualize locations of cultural heritage sites.

The system consolidates information from a broad network of contributors – military reconnaissance units, civilian authorities, international intelligence partners, and verified observers. Data streams come from commercial and military drones, ground sensors, satellite imagery, and intelligence provided by partner nations. All inputs are georeferenced and displayed in real time, often accompanied by imagery of enemy equipment and activity.

Following Russia's full-scale invasion of Ukraine, DELTA's role for frontline forces expanded dramatically. New features have been introduced based on direct feedback from operational users. This iterative development process allows the DELTA team to rapidly implement updates that meet the evolving needs of combat units – enhancing targeting precision, force protection, and coordination – while, whenever possible, upholding Ukraine's commitments

under the 1954 Hague Convention and its two Protocols to mitigate risks to cultural heritage during military operations.

Today, DELTA provides the Ukrainian Armed Forces with:

- real-time situational awareness;
- live video feeds from Unmanned Aerial Systems and fixed cameras;
- secure communications and chat tools;
- planning utilities and synchronization matrices for reconnaissance and target acquisition;
- integration with robotic and automated systems;
- a dedicated Cultural Heritage layer for safeguarding protected sites.

At present, the Central Directorate of Civil-Military Cooperation of the General Staff of the Armed Forces of Ukraine has begun preparing data on archaeological sites in Ukraine (over 60,000 objects) for further import into the cultural values information layer of the Delta situational awareness system. Another pressing task is to create a database of cultural objects of global, national and local significance that have historical, architectural and spiritual value and are located in the temporarily occupied territories, with regular updates on their condition and status. Representatives of the cultural heritage protection unit, which was established within the structure of the Armed Forces of Ukraine at the end of 2024, will participate in the implementation of this task.

These measures demonstrate Ukraine's intention to continue to comply with its previous commitments under the provisions of the 1954 Hague Convention and its two protocols in the context of protecting cultural property during wartime.

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## 111. Photogrammetry as a tool for preserving cultural heritage: the example of artifacts from the medieval steppes of Ukraine

*Yaroslav Chentsov (Odesa National Scientific Library)*

The issue of preserving Ukraine's cultural heritage in the context of the Russian-Ukrainian war, which has been ongoing since 2014, is incredibly relevant. The hostilities are destructive in nature and are physically destroying the cultural heritage of the Ukrainian people. This also applies to archaeological sites located in the conflict zone. This report will focus on the monuments of the medieval nomads of the Ukrainian steppe, as burial mounds, which are almost the only archaeological expression of this community, are under particular threat. Burial mounds occupy a dominant geographical position in the flat steppe and are convenient locations for active combat operations. They also suffer at the hands of illegal looters who take advantage of the ban on official excavations of burial mounds without good reason, in order to prevent the disappearance of the monument itself as a unique object of Ukrainian history. Archaeological collections stored in museums in modern Ukraine that found themselves in the zone of combat operations or occupation during the Russian invasion are also vulnerable. Examples include the appropriation of significant collections from the Donetsk Regional Museum in 2014 and the damage and destruction of Cuman stone sculptures (so-called "babas") on Mount Kremenets near the city of Izyum in 2022, the removal of artifacts from the Kamyana Mohyla Museum, etc. One of the means of combating this situation is photogrammetry. The potential of photogrammetric research is fully revealed in combination with other disciplinary studies that provide the apparatus for interpreting the obtained data. The virtual representation of artifacts belonging to medieval nomads in the territory of modern Ukraine, given the current situation, emphasizes the need for digitization, including three-dimensional digitization, of numerous

Ukrainian archaeological collections and sites. Even unique materials and materials important for attribution require better documentation and more complete representation. Therefore, it is precisely these materials that will serve as demonstration samples for this report. This is a series of artifacts provided by the Odesa Archaeological Museum of the National Academy of Sciences of Ukraine and the Dnipropetrovsk National Historical Museum named after D. I. Yavornytskyi, which represent the medieval nomads of the Ukrainian steppe and, in some cases, convey their ethnic or political affiliation. These artifacts include straight bits, which indicate the Pecheneg ethnic group; arrowheads, which mark the period of the Ulug Ulus in the Ukrainian steppe; pottery from medieval urban centers, which was found in nomadic burials; and others. All of them have been digitized and presented in the form of 3-D models. As for photogrammetric methods and their integration into archaeological research, it is extremely important to create opportunities for interdisciplinary dialogue. Currently, archaeological scientific publications using modern technical approaches, including photogrammetry, are only beginning to appear in Ukraine. Meanwhile, the creation of 3-D collections of artifacts of medieval nomads, in addition to preserving their digital copies, provides advantages for scientific work. High resolution and maximum accuracy allow for the creation of a sample that greatly simplifies the typology and classification of archaeological material, which, unfortunately, has not been fully processed by Ukrainian archaeologists. In the context of medieval nomads, this is especially important due to the low level of study of the topic among contemporary Ukrainian archaeologists. The findings of large-scale soviet expeditions have not yet been fully analyzed, and the work of the contemporaries of these expeditions is methodologically outdated.

Therefore, preserving Ukraine's archaeological heritage in the context of the ongoing Russian-Ukrainian war is one of the most pressing challenges of our time. The destruction of medieval nomadic steppe monuments not only deprives scientists of important sources for reconstructing the historical past, but also causes irreparable losses. The use of photogrammetry as a tool for recording, researching, and virtually representing artifacts opens up new opportunities for their preservation, interpretation, and popularization. The



integration of digital technologies into archaeological studies contributes to the formation of an interdisciplinary space for interaction between specialists, expands access to data, and ensures the continuity of scientific work even in crisis conditions. Therefore, the systematic introduction of photogrammetric methods into the study and digitization of archaeological collections is an essential component of the modern strategy for preserving Ukraine's cultural heritage.

### 305. The fate of the Neolithic Mariupol cemetery: evidence of the crimes of the Russian occupiers)

*Nataliia Mykhailova (National Academy of Sciences of Ukraine)*

The Neolithic Mariupol Cemetery, excavated in 1930 by famous Ukrainian archaeologist M. Makarenko, is one of the most important burial sites in Ukraine and Eastern Europe, unique in the richness and variety of its finds. There were 124 graves in the cemetery. The rests of the people formed separate multi-level clusters. The skeletons lay parallel to each other within the strip. Most of the buried were in supine position, abundantly covered by red ochre.

An unusual abundance of burial inventory was found with many of the deceased, both men and women. Some burials were accompanied by symbols of power, such as maces.

The materials provide a wealth of information about the spiritual world, social structure, gender relations, and burial rites of the Neolithic population of Eastern Europe. The extraordinary richness of the burial goods, the large number of high status burials (including those of children) and the abundance of unique adornments, could occupy many generations of scholars.

The most impressive personal ornaments are perforated boar tusks. The plurality of these decorations in Mariupol Cemetery determines the uniqueness of this funeral complex.

The Mariupol burial ground gave its name to a whole series of Mesolithic and Neolithic sites, most of which were located in the Lower Dnieper region. These sites are characterised by similar burial rituals and identical decorations, including a large quantities of red deer and carp teeth, boar tusk plates, and mother-of-pearl and stone necklaces.

Although the Mariupol burial ground materials became unavailable for study in Ukraine in 2022, the author and Marian Vanhaeren (CNRS, France) began digitally processing jewellery from Mariupol-type burial grounds. The result of the work should be a catalog of Mariupol-type burial mound jewelry.

In 2022, hundreds of thousands of Russian troops launched a brutal and senseless invasion of Ukraine, a peaceful country. In April 2022, during the fierce battles for Mariupol, the Russian occupation forces shelled the Local History Museum. The wooden floors of the building were burnt. The unique collection was destroyed by the Russian occupiers. The remained artifacts were stolen.

The destruction of materials from the Mariupol burial ground is just one of the many crimes that Russian invaders have committed against Ukrainian heritage.

### 318. Digital Preservation as Mitigation: Photogrammetric Documentation

*Kseniia Lishchyna (The Odesa I.I.Mechnykov National University)*

The rapid intensification of military conflicts and environmental threats puts world archaeological heritage sites at increased risk. In active danger zones, particularly in Ukraine, digital documentation is transforming from an auxiliary academic tool into an urgent mitigation strategy against irreversible loss. Traditional recording methods, such as 2D photographs and hand drawings, are insufficient because they are subjective and unable to convey the full spatial geometry, texture, and structural characteristics of objects. In the

event of the destruction of a physical artefact, such 2D data leaves behind an incomplete and often misleading record.

This work examines the critical function of three-dimensional spatial reconstruction in the preservation of complex archaeological art (e.g., petroglyphs, frescoes, mosaics). It can be argued that the creation of high-precision digital surrogates is an important preventive measure for protecting cultural information when the physical objects themselves are threatened with destruction. This approach, which underlies 'virtual archaeology,' allows us to move from the statement 'it was destroyed, so it is gone forever' to the active preservation of at least an accurate digital copy for future generations.

In this study, terrestrial (close-range) photogrammetry was used as the primary data collection method. This method was chosen for its cost-effectiveness, mobility, non-invasiveness, and high speed in the field. Unlike laser 3D scanning, which requires expensive and bulky equipment, photogrammetry allows highly detailed models to be obtained using standard digital single-lens reflex (DSLR) cameras and affordable software (e.g., Agisoft Metashape).

This makes it an ideal tool for archaeological expeditions working under time constraints, limited funding, or complex logistical constraints typical of high-risk areas.

If physical heritage is damaged or destroyed as a result of bombing, looting or environmental collapse, these models will ensure that its essential spatial and visual information is preserved. They serve as a permanent, analysable archive for future research, virtual reconstruction and public engagement (e.g. through virtual museums) This work demonstrates that systematic 3D documentation of heritage in endangered areas is an important ethical and scientific responsibility to mitigate irreversible cultural losses.

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### 355. From ramparts to trenches. Digital documentation of belligerent landscapes in wartime Ukraine (case study of Bilhorod-Kyivskyi hillfort)

*Oleksandra Ivanova (National university "Kyiv-Mohyla academy")*

*Ivan Zotsenko (Institute of Archaeology NAS of Ukraine)*

In June 2025, the expedition of the Institute of Archaeology of the National Academy of Sciences of Ukraine, conducted excavations at the site of the medieval city of Bilhorod (modern Bilohorodka, Kyiv region). After the onset of Russia's full-scale invasion in 2022, the hillfort once again gained strategic importance: Ukrainian forces built defensive trenches there to halt the Russian advance toward Kyiv. These trenches cut directly through the archaeological layers of the Kyivan Rus hillfort, which had itself been constructed over a thousand years ago to protect Kyiv from western incursions. Such spatial continuity in the use of the same landscape for defense exemplifies the persistence of belligerent landscapes.

Following the withdrawal of military units, archaeologists gained access to the site. From 2023 to 2025, rescue excavations were conducted with the

goal of documenting and preserving areas of the cultural layer damaged by modern fortifications. During the 2025 season, a section of the 2022 trench was examined where it cut through features of the Kyivan Rus period: a stove, a dwelling structure, and partially intersected a 19th-century house. The fieldwork incorporated extensive digital documentation using photogrammetry and laser total station surveying. Image processing and 3D reconstruction were performed with Capture One and RealityCapture. The resulting models include the trench, the early medieval features, and the 19th-century dwelling. The 3D models of the stove and the house are publicly available on the Sketchfab page of the Scientific and Research Lab Archaic ([https://sketchfab.com/lab\\_archaic](https://sketchfab.com/lab_archaic)).

Digital recording made it possible to trace subtle structural and stratigraphic relationships and to document the stove's construction and dismantling in detail. This level of precision provided new insights into building techniques and the preservation of ancient structures partially disturbed by modern activity. Equally significant was the observation that the backfill from the 2022 trench has already begun to behave like an archaeological layer: after three years, it had compacted and been covered by new excavation deposits, effectively becoming part of the site's stratigraphy.

The Bilhorod-Kyivskyi case raises important questions about how contemporary defensive structures should be interpreted, whether as destruction or as a renewed use of space for the same purpose. The modern trench that cuts through the ancient ditch demonstrates the enduring reuse of a defensive landscape to protect Kyiv across centuries. Digital methods allow not only for the preservation of these complex layers through high-resolution 3D models but also for deeper analysis of the spatial and temporal continuities of warfare.

After excavation, the investigated section was conserved using geotextile to prevent further degradation. In the next field season, research will continue on other sections of the remaining open trenches, with the aim of conserving

exposed cultural layers and creating a comprehensive digital archive of the site. Thus, the Bilhorod-Kyivskyi hillfort is being preserved both physically and digitally as a testament to the enduring defensive landscapes of Ukraine.

## 427. From Documentation to Digital Narratives: Transforming the Odesa Archaeological Museum

*Mariia Lobanova (Odesa Archaeological Museum of the NAS of Ukraine)*

*Oksana Hrytsiuta (Odesa Archaeological Museum of the NAS of Ukraine)*

Since the beginning of the full-scale invasion of Ukraine, the Odesa Archaeological Museum has faced severe risks to its collections, archives, and infrastructure. In response, and with the support of international partners, the museum initiated a large-scale digitization strategy focused on photographic documentation, photogrammetry, and the long-term preservation of digital archaeological data.

Photogrammetry served as a core documentation method within several digitization initiatives, including the Ukrainian Heritage Digitization and Dissemination Initiative, launched by the Archaic Research Laboratory in collaboration with CyArk. During the second phase of the project, the Odesa Archaeological Museum digitized selected artefacts representing the diversity of its collections – from Palaeolithic tools and Cucuteni-Trypillia figurines to ancient and medieval ceramics, marble sculpture, and architectural fragments. In parallel, laser scanning was applied to document the museum building and a section of the Odesa Catacombs.

Alongside 3D model production, systematic collection of paradata and metadata was implemented throughout the workflow. This included technical documentation of photogrammetric processes, recording of acquisition parameters, processing steps, and descriptive object attributes to ensure long-term reusability, traceability, and scholarly transparency of the digital assets.

To support sustainable data storage and management, the museum established a dedicated digital infrastructure. Through a House of Europe grant supported by the European Union, the Odesa Archaeological Museum acquired a server and equipped a specialized server room. All generated datasets – including 3D models, associated paradata and metadata, and digitized archival documentation – are currently stored on this local server. As a next step, the museum is evaluating the integration of cloud-based storage solutions to provide additional redundancy and enhanced protection for its most critical digital heritage data. These digital assets are actively used in research, virtual exhibitions, and interactive educational projects.

The Archaic Research Laboratory also contributed to the digitization of 12 heritage objects from Zmiinyi Island, a heavily shelled site where the museum's branch was destroyed, and supported the 2024 exhibition "Zmiinyi: The Island Protected by the Gods".

Beyond immediate preservation outcomes, the project demonstrates how digitization workflows, metadata management, and local digital infrastructure can strengthen institutional resilience during armed conflict. The integration of photogrammetry into academic teaching at Odesa I. I. Mechnikov National University further extended the project's impact, allowing students to acquire practical digital skills while producing reusable research data. The preparation of a joint virtual exhibition with partner institutions highlights the potential of aggregated 3D collections to create new digital narratives, expand access to endangered heritage, and promote Ukrainian archaeology internationally.