



Building blocks between past and present: Perspectives from a holistic 3D GIS-based intra-site excavation archive[☆]

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ABSTRACT

This paper summarises the development and showcases the uses of a 3D GIS-based tool used by the Keros Project in our work at the Early Bronze Age site of Dhaskalio, Keros. While reflexivity and born-digital tools were built into the design of the more recent 2016–2018 excavations, the earlier 2006–2008 seasons were limited to the techniques available at the time. This has led us to address how to appropriately integrate older non-natively digital excavation material into an extensive 3D environment in a way in which specialist and artefact data, stratigraphic information and architectural material can appropriately be analysed together and made accessible to team members in a single environment. The extrapolation of photogrammetric models and orthomosaics from archival excavation photos from the 2006–2008 seasons, and incorporation of 3D finds and specialist data has been a key challenge. The synthesis of old and new data from a project archive based on disparate sources in such a 3D environment has offered many benefits: first, a contribution to the role of reflexivity in excavation practices and site interpretation, and second, a better comprehension of the site overall, especially from an architectural perspective. In particular, bringing together 3D models of building remains which had been backfilled, and were thus inaccessible to those working in the most recent excavations, has been invaluable to our understanding of the site. Furthermore, such work has facilitated the production of new data in 3D reconstructions of the different occupation phases. This paper addresses some of the methodological and theoretical issues faced when attempting to incorporate such diverse data into a single access point, in particular with reference to 3D data, in the hope of continuing a dialogue on best practices for long-term single project archives in a period of increasingly born-digital data.

1. Introduction

1.1. Site history

The Early Cycladic (c. 3300 – 2200 BCE) site of Dhaskalio is situated on a small and steep islet, less than a hundred metres to the west of the promontory of Kavos, at the western tip of the island of Keros, Greece (Renfrew et al., 2013), noted for its numerous broken marble figurines and vessels (Renfrew et al., 2012; 2013; 2015; 2018). In the Early Cycladic period, Dhaskalio was linked to Kavos by a now submerged isthmus (Dixon and Kinnaid, 2013). The sites first came to the attention of researchers in the 1960 s after an episode of looting at Kavos.

Following this, small-scale excavations on Dhaskalio were undertaken on-site under the direction of C. Doulas (Doulas, 1964; 2007; 2013) as part of a rescue operation focused mainly on Kavos, followed by much more extensive field work between 2007 and 2008 (Renfrew et al., 2013). These operations revealed the existence of a large and densely built Early Cycladic architectural complex (Boyd, 2013). This was more extensively explored during a second campaign, carried out between 2016 and 2018 (Renfrew et al., 2022). The pottery and radiocarbon dates so far indicate a long occupation of the settlement from ca. 2800 BCE to ca. 2200 BCE. The settlement covers approximately 1.3 ha and appears to be particularly densely built. It was constructed on the naturally steep and rocky landscape by means of an impressive site-scale

Abbreviations: BIM, Building Information Modelling; CIF, Central Information Framework; EC, Early Cycladic; GCP, Ground Control Point; MR, Mixed Reality; SfM, Structure from motion; UAV, Unmanned Aerial Vehicle; VR, Virtual Reality.

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concentric terracing system encircling the islet below the summit on the north, east and south sides (Fig. 1; Floquet, 2024). The overall layout takes an approximately radiocentric form, dictated by the natural topography and the construction of the terracing system. The routes of movement, composed of concentric or radial streets built on drainage systems, followed this general plan.

1.2. A living database

While the exploration of the site revealed a large sample of finds and architectural remains, the evolution of the recording methodology used over the span of more than a decade led to the production of disparate documentation, which could not provide the level of overall coherence desired by the project. Previous research methodologies developed by this project (Boyd et al., 2021) culminated in the development of a holistic 3D GIS solution (Campbell et al., 2024), which incorporated all facets of excavation and specialist data, including more than a thousand 3D models, with the intention that this would act as a 'living' database and project archive. The nature of archaeological projects means that a myriad of rich post-fieldwork data continues to be produced years after the excavation has finished. This is made more complex with ongoing and long-term projects, where the necessity to re-engage with excavation material is paramount, yet hindered by a mix of technologies and techniques used for recording, and often made difficult to access through incompatible software, visual formats, or paper. This has therefore

encouraged us to review the earlier 2007–8 excavations in order to digitise and transform the material into a format that is compatible with the newly established fine-grained, three-dimensional data structure. The result is a comprehensive 'living' 3D archive, where users are able to query, curate, and analyse multiple years of excavations and research in a single system.

1.3. Archaeological 3D GIS as an intra-site archive

During the 2007–8 excavation seasons, the project first began experimenting with the use of unmanned aerial vehicles (UAV) for the production of high resolution orthoimages (Patias et al., 2009). The larger scale excavations conducted from 2016 to 2018 incorporated a new methodological framework rethinking the documentation strategies, in-field scientific approaches, and data management practices (Boyd et al., 2021). One aspect of this was an entirely digital recording process that included replacing field drawings with photogrammetric models (Boyd et al., 2021; Campbell et al., 2024).

The importance of 3D GIS for archaeological excavations has been discussed for twenty years and is by now well established (Merlo, 2004; Merlo and Shell, 2005; Berggren et al., 2015; Dell'Unto and Landeschi, 2022). Organisation and reflexivity in the use of 3D GIS have remained a chief concern, particularly when it is being used as a 'living document' (Katsianis et al., 2021). As noted by Merlo (2016), three-dimensional GIS can allow for a more nuanced understanding of the excavated

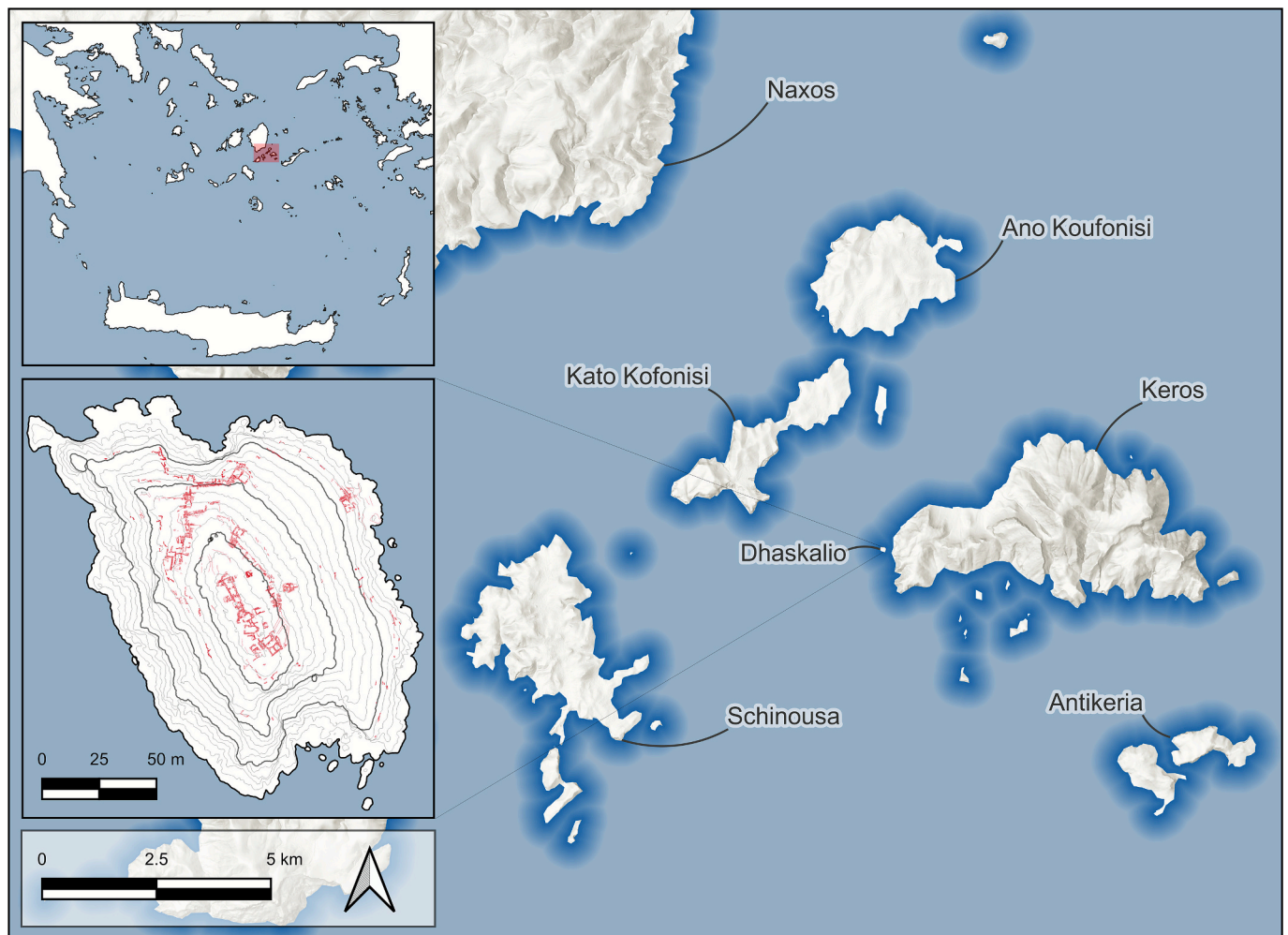


Fig. 1. Dhaskalio and Keros in their regional context in the southern Aegean. Red lines on Dhaskalio indicate architecture. (Map design by R. Campbell and H. Indgjerd, the Keros Project; basemap uses Esri World Hillshade with data from Esri, TomTom, Garmin, NGA, METI/NASA, USGS. Copyright © 2025 Esri and its licensors. All rights reserved.).

archaeological record, particularly when using spatial and temporal data in synthesis. The multidimensionality of 3D GIS environments has the opportunity to enhance the understanding of site dynamics, as it allows for the study of phenomena determined by stratigraphic laws, with the added value of seeing finds and samples in a modelled volume rather than in plan or section.

While the principles of photogrammetric modelling have been known for a long time (Schenk, 2005: 7-9; Fritsch, 2005), the expense of photography and limitations on computing power and available software restricted the implementation of large-scale photogrammetry-based 3D recording until the previous decade. As photographic documentation prior to this was seldom made with 3D modelling in mind, the feasibility of using such datasets as the basis of a 3D GIS may seem uncertain. There are, however, cases where legacy photographs have been successfully processed into 3D models, especially using already structured and overlapping aerial mapping imagery for the creation of historic DEMs of landscapes (for example in Italy: Sevara et al., 2018; Poggi, 2021, and in Norway: Risbøl et al., 2015).

Retrospective photogrammetry of archaeological monuments and excavation sites in Greece has been successfully undertaken by Wallace (2017) at Corinth and the Athenian Agora, while Katsianis et al. (2021) proved the applicability of the method on surfaces of stratigraphic units from ordinary context recording photographs. A pioneer of 3D modelling in archaeology, Katsianis was aware of the possibilities of photogrammetry, and ensured the project already did overlapping photography for orthomosaic generation (Katsianis et al., 2021:2). This dataset was likely particularly well suited for retrospective modelling, and not a guarantee the technique would work at other excavations. Photogrammetry and 3D modelling based on legacy data has recently also been implemented in South Africa (Unhammer et al., 2024) and in the USA (Bischoff and Allison, 2023). At the predominately Middle Palaeolithic Blombos Cave excavation, Unhammer et al. focussed on reconstructing stratigraphic profiles using more than 6000 analogue and digital documentation photos from the first 30 years of work at the site, and combined the 59 resulting models with plotted artefact locations into a 3D GIS. Interestingly, they note higher quality results from analogue 35 mm slides captured in the 1990s than from the digital photographs of the early 2000s, but found the lack of embedded meta-data complicated the Structure from Motion (SfM) camera alignment (Unhammer et al., 2024:10-11).

2. Material and methods

2.1. The central information framework

The data infrastructure of the Keros excavations, known as the central information framework (CIF), is hosted on a remote server accessible online via a VPN connection. This ensures accessibility by limiting the users' hardware and software requirements to an internet connection and tools built into all major operating systems. The project data are organised around a PostgreSQL database with additional file storage for object data. The information in this single backend can be accessed with a variety of frontend tools, serving different use cases, user skills and analytical tasks (Fig. 2). An important effect of this is that data edited on one system, for example zoological analysis entered in an Access form or 2D polygon shapes altered in QGIS, will immediately be visible for users of other platforms, thus avoiding knowledge silos between different specialists' data management traditions. Specialists are able to use the software they feel most comfortable with, but are encouraged to explore their data in the 3D GIS, using ArcGIS Pro for its advanced 3D capabilities. As one accesses the GIS by remote desktop, all that is required is a stable internet connection. This means that one can look at the data collected during the excavation in 3D and traditional 2D GIS environments, as well as through tabular and form data input interfaces. A detailed overview of this methodology is published elsewhere (Campbell et al., 2024).

The Central Information Framework allows users to access the excavation documentation and post excavation analyses from specialists, within a single holistic environment (Fig. 3). The 3D capabilities give the user several different levels of analysis, from site wide perspectives to the context level, and stratigraphic levels of analysis. As each stratigraphic model contains the data recorded by the iDig iOS app (see Boyd et al., 2021) for field recording during the excavation, including a timestamp, it is possible to use the GIS's *time* function to look at which contexts were open on specific days and digitally reconstruct the timeline and conduct of excavation of the site itself. As already noted, (Campbell et al., 2024), this could be particularly valuable in terms of reflexivity and accountability in excavation practices. Wherever possible, all 3D and shape data are related to the phases of the site in its attribute table. By having pre-set queries in the system, one can easily analyse specialist data, exemplified here by the distribution of sherds belonging to several macroscopic ceramic groups, queried to view the quantity of sherds in two phases (Fig. 4).

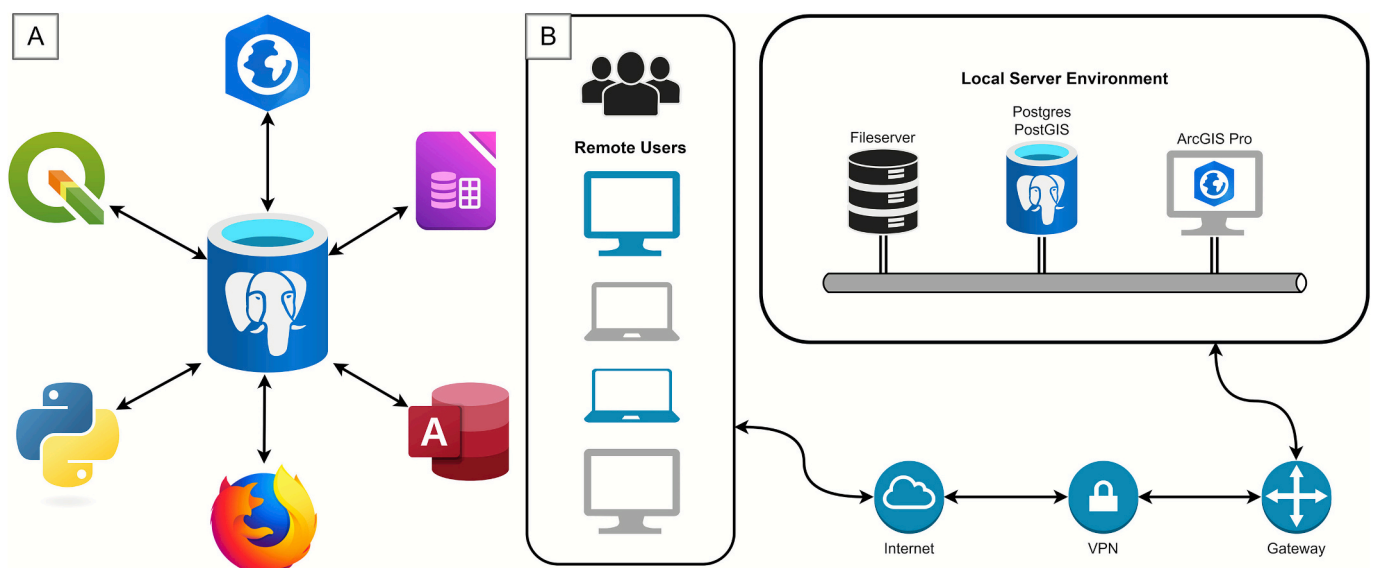


Fig. 2. Mapping of the infrastructure (illustration by H. Indgjerd).

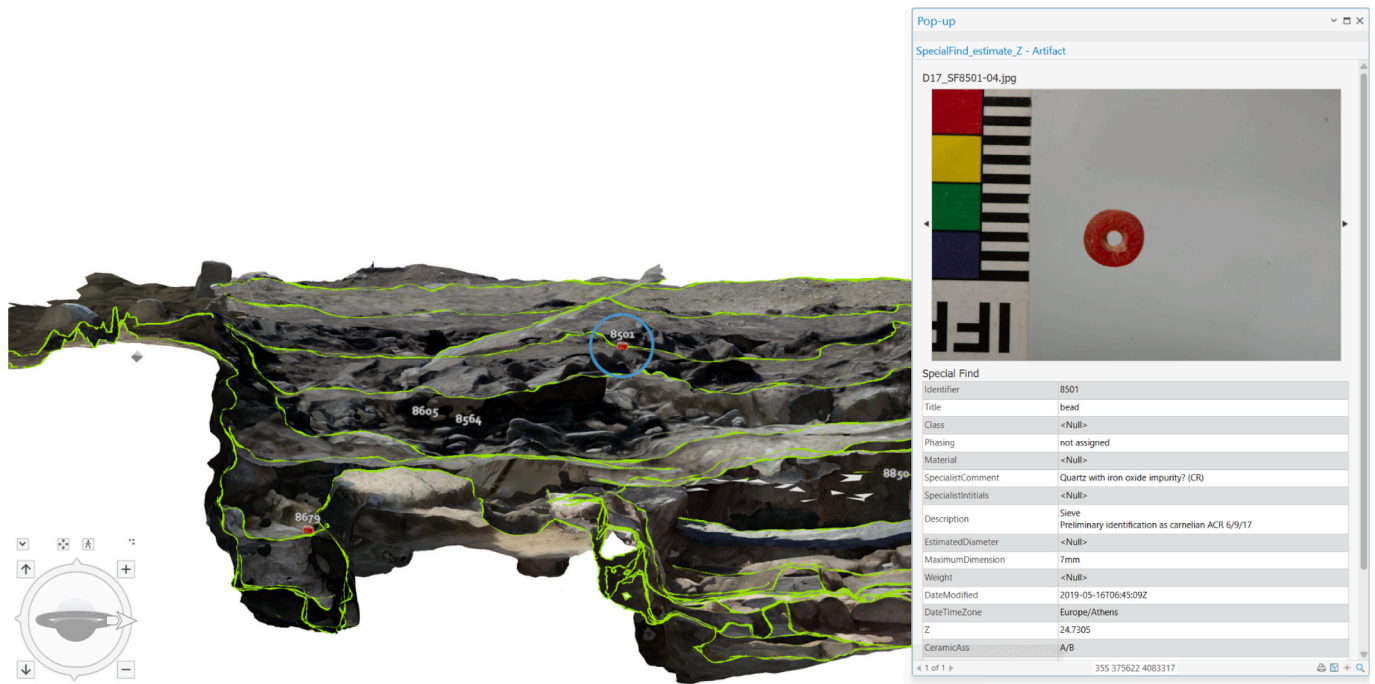


Fig. 3. View of the GIS environment, filtered to show beads and stratigraphy from Trench N (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

2.2. Integrating non-natively digital and analogue data with born-digital data

The integration of analogue data into the established Central Information Framework has now become a principal objective of the project's intra-site 'living' archive. This includes all excavation material recorded in the 2007 to 2008 seasons on Dhaskalio, including digitisation where necessary, and the systematic extraction of georeferenced data. Several layers of data from these earlier excavations have been integrated into the 3D environment. This includes the photogrammetric models and ortho mosaics extrapolated from archival excavation photos, as well as polygons for each context based on stratigraphy from photographs and drawings, and the special finds data incorporated with their measured-in point locations.

2.2.1. Retrospective photogrammetry

Fortunately, during the 2007–8 seasons, the project experimented with photogrammetric methods (Patias et al., 2009), including aerial photographs of the entire islet taken from a UAV, and photographs of each trench taken from a camera mounted on a pole. As the 2007–8 photogrammetry programme was experimental in nature, there were several limitations. Aiming to produce mosaic imagery rather than 3D models, the workflow did not include georeferenced target points, the image quality and number of photographs taken was restricted by the technology available, and the nadir angle from which photographs were taken were not optimal for detailed 3D imagery of vertical architecture. Even so, these datasets have enabled us to reprocess images with the intention of producing 3D models to be integrated into the established 3D GIS, in part due to the steep terrain of Dhaskalio, which inadvertently captured oblique shots of the trenches and provided enough angular diversity for SfM to triangulate 3D points. To do so, spatial data recorded in the 2016–18 seasons was used to act as reference 'targets' in the 2007–8 photographs (Fig. 5). For example, the corner of a stone in a wall that had been undisturbed between seasons, or the tip of a crack in the bedrock that was visible in each image, were measured in the georeferenced 2016–18 model, where the XYZ coordinates were then given to the target point placed in the photogrammetry software during the

reprocessing of the 2007–8 images. After producing the now georeferenced 3D model, additional alignment to the 2016–18 data were then completed in CloudCompare, where overlapping architectural elements and bedrock outcrops were used as reference data. While the precision of this output is lower than in our standard workflow, this method has allowed us to produce 3D models of each trench that are accurate enough to be used seamlessly with the 2016–18 data within the GIS.

2.2.2. Extracting 3D from analogue archives

The integration of the 2006–8 archives into the system followed a methodology established by Katsianis et al. (2008, 2021), where the digitisation and georeferencing of hand-drawn plans was used to trace excavation units as polygons, using the levels taken during the excavations to give height values for each layer. This allowed a reconstruction of the excavated stratigraphic units in 3D. Similarly, section drawings were fit into the 3D space directly in ArcGIS Pro by creating a three-dimensional block in the measurements of a section drawing and using the drawing as a texture, fitting it into place (Fig. 6). In the earlier excavations, artefact and specialist data was recorded using a dumpy level and a baseline offset, taken from the corner of each trench. The location of each find was converted into XYZ points in the GIS, and joined with the information recorded by specialists.

A key part of the digital recording methodology from 2016 was the use of photogrammetric recording of each context pre- and post-excavation (Boyd et al., 2021, 2022, Campbell et al., 2024). The added value of integrating realistic representations of contexts for post-excavation analysis became clear where, for example, undulations, slopes, and small changes in strata surfaces are apparent in the photogrammetric models, but are missing in the digitised 3D polygon (Fig. 7, Schubert et al., 2018 show the issues of relying on profile drawings for the extrapolation of 3d surfaces). With this in mind, we prioritised creating georeferenced 3D models of each layer excavated in 2007–8 from photographs taken during the opening and closing of layers in the excavation. These were often taken with enough differentiation in angles to allow for a successful photogrammetric reconstruction (Fig. 8). The limited quantity of photos (generally between three and six), however, meant that masking was generally not possible, resulting in

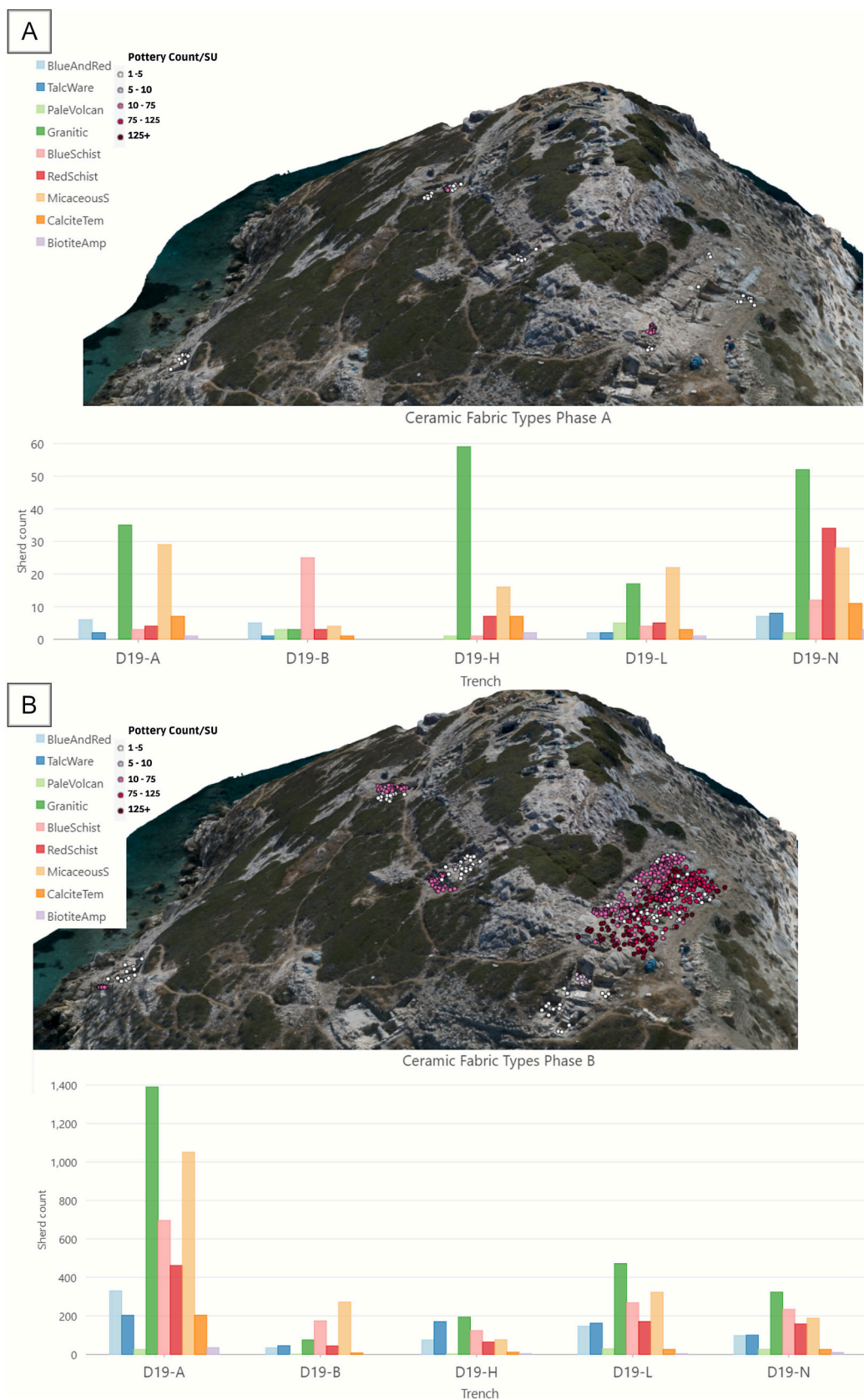


Fig. 4. Distribution of ceramic fabric types across the site in Phase A and Phase B (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

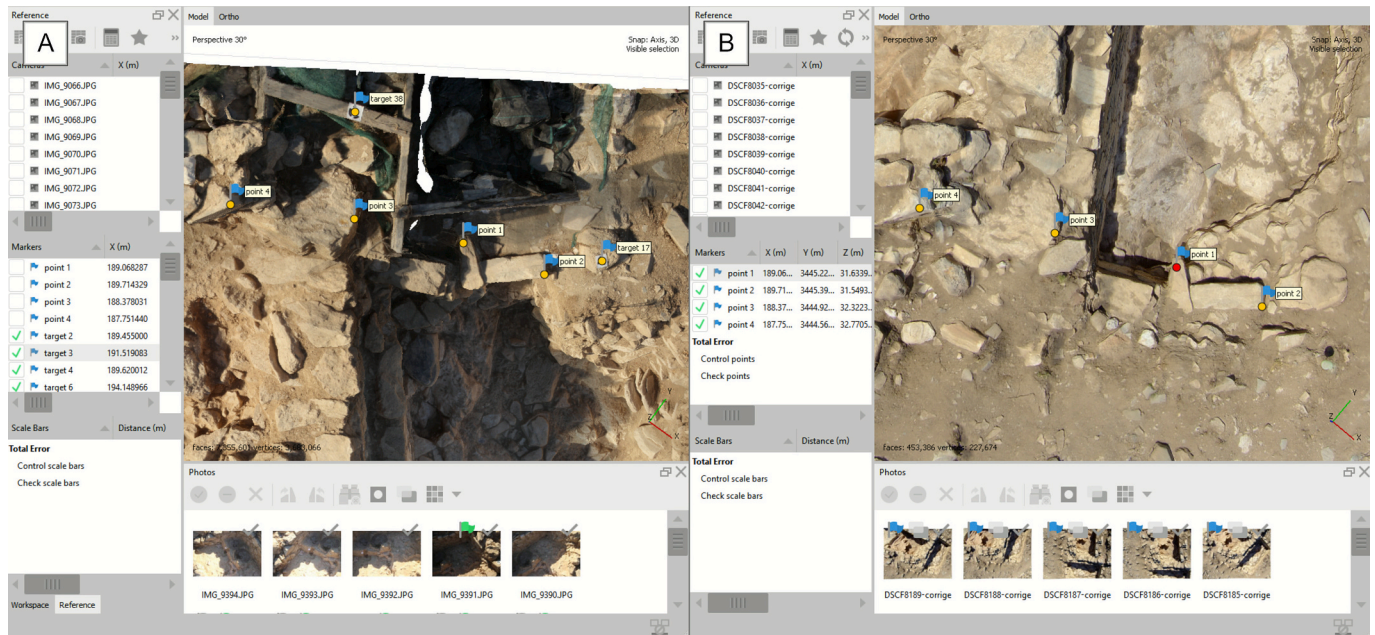


Fig. 5. Georeferencing (a) 2007–8 photogrammetry using (b) visible architecture of the site in 2018 (screenshot from Agisoft Metashape, illustration by R. Campbell, the Keros Project).

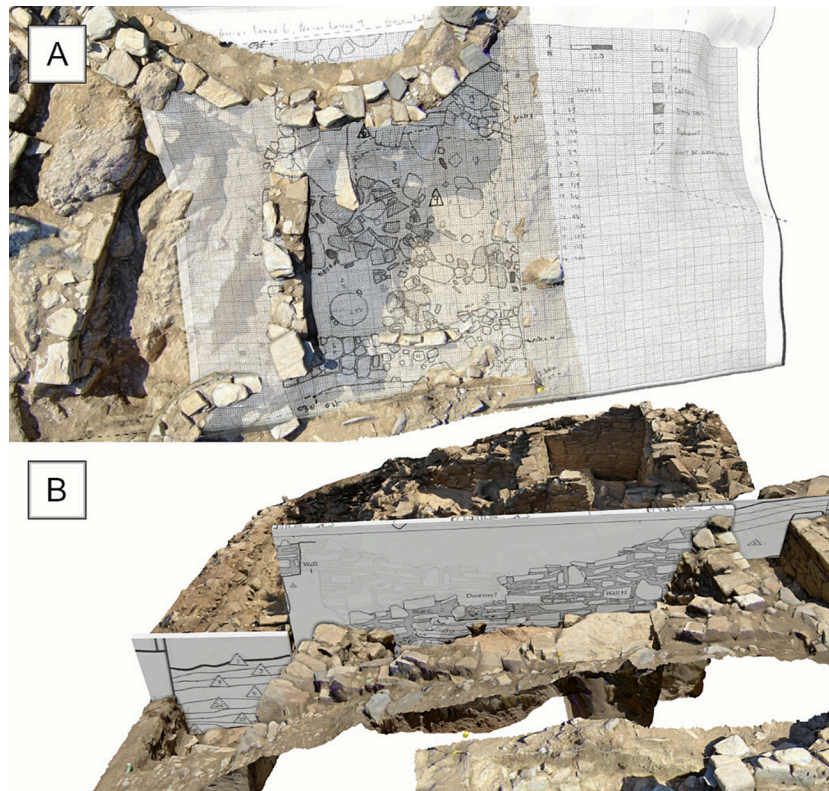


Fig. 6. Georeferenced plans, sections, and excavation unit polygons in the 3D GIS environment (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

the presence of ghosting from the context identification board and ranging-rod. Each stratigraphic layer model was georeferenced by aligning it with the visible architecture from within the trench using CloudCompare, and then cropping each model to the polygon size (itself based on the digitised trench plans, as discussed above). Due to the limited number of photographs taken of each excavation unit between

2006 and 2008, it was not always possible to reconstruct each layer successfully. For those where retrospective photogrammetry was unsuccessful, the polygon created from drawing is used in its place. Each excavation unit was then joined with the corresponding context information.



Fig. 7. Trench VII, layer 32 as polygon (a), retrospective 3D model (b), and combined (c). Note that the ranging-rod is apparent in the photogrammetric reconstruction (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

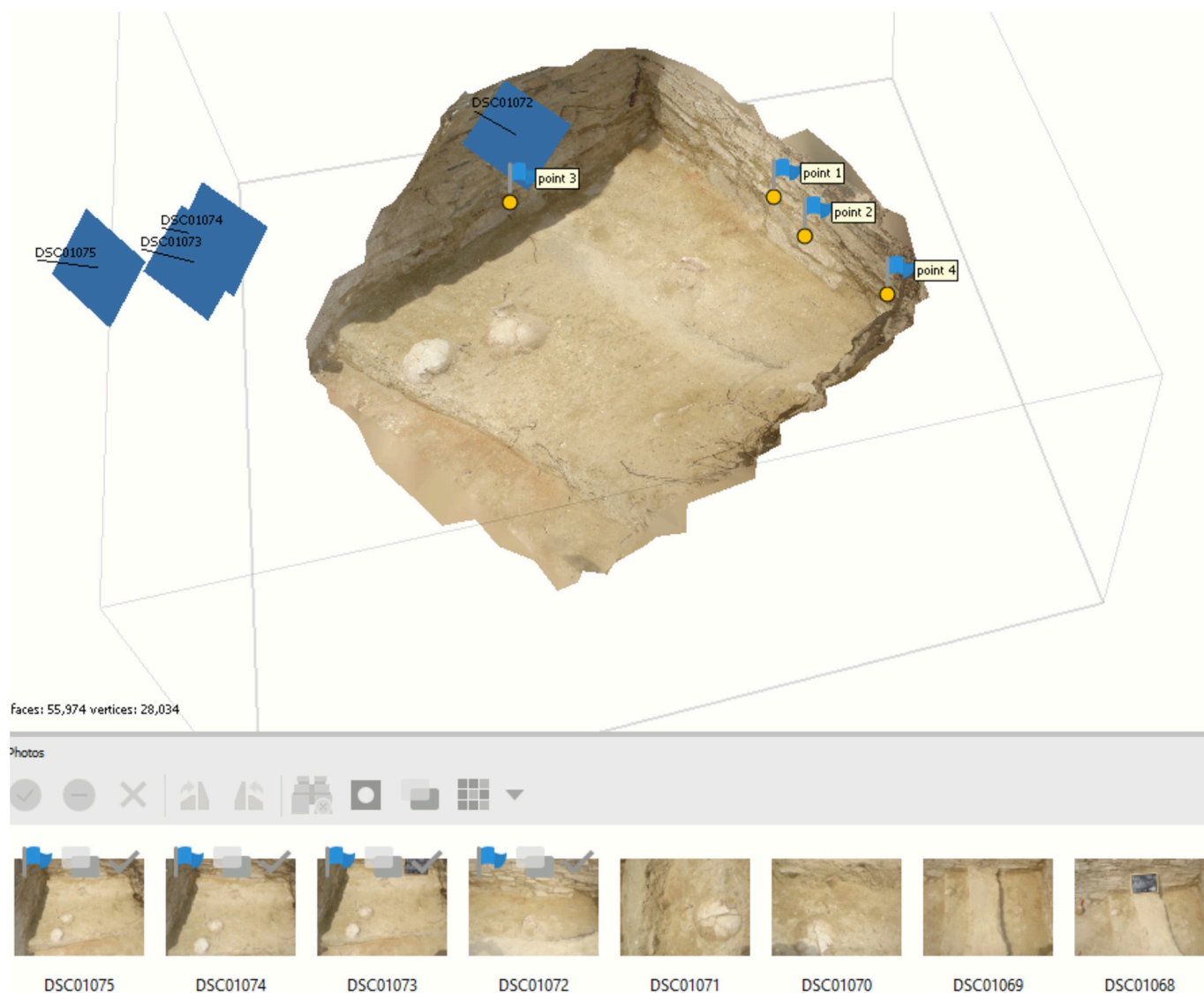


Fig. 8. Reconstruction of layer 36 of Trench VII in Agisoft Metashape (R. Campbell, the Keros Project).

2.3. Architectural reconstructions

Based on the photogrammetric programme, we have produced 3D reconstructions of architecture from structures investigated both during

the 2007–8 and the 2016–18 excavations. These reconstructed built spaces were integrated into the 3D GIS environment together with the excavation data, leading to the creation of a complete 3D environment of the settlement combining physical remains and reconstructions based

on archaeological interpretation (Fig. 9).

2.3.1. Modelling methodology

The 3D models were built from plans and orthomosaics of the trenches using Sketchup, an intuitive 3D modelling and Building Information Modelling (BIM) software commonly used to create idealised architectural 3D sketches. The models were then exported to the open source 3D creation suite Blender, to generate improved textures, lighting, and elevation details. Texture, level of detail, and opacity of the produced models can be adapted depending on the use case and intended audience. A simplified, semi-transparent rendering is used in the 3D GIS to highlight its interpretive nature and set it apart from the recorded physical data (Fig. 10a), while immersive and VR-ready environments are created by adding in more realistic textures, light sources and perishable objects (Fig. 10b).

2.3.2. Interpretive choices

The scientific validity of the 3D reconstructions is founded on two key elements. First, the careful stratigraphic sequencing, developed on-site during the excavation using a single-context, open-area methodology (Boyd et al., 2021), allowed us to identify clear architectural phases in each trench. In the case of Trench H (Fig. 10b), three phases were noted, characterized by a noticeable change in architecture, spatial arrangement and use. Second, the reconstruction of the missing or undetectable architectural elements, such as wall elevations, doors, windows, and roofs, is based on current knowledge of building techniques in the Early Bronze Age Cyclades (Floquet, 2024; Gkouma et al., 2022; Economidou, 1993; Doumas, 1972; Stampolidis and Sotirakopoulou, 2011; Boyd, 2013; Marthari, 2018). The height of the buildings at Dhaskalio is estimated to be approximately 2 m. This is based both on the extensive terracing system of the site, which broadly required the rooftop to be at the same level as the adjacent upper terrace floor, and on direct observations of fully preserved two-storey buildings in the partly contemporaneous settlement of Skarkos on Ios (Marthari, 2018). While very few windows are preserved, the numerous doorways identified on-site allows us to accurately reconstruct the routes of movement toward and inside the buildings. While the doors have decomposed (they were presumably made from wood and are therefore not preserved), the stone pivots found in the corners of many door thresholds enable us to infer the placement and design of the door closing system. Finally, the roofs are thought to have been mostly flat, made of a wooden frame placed on the upper parts of the building's stone walls, and covered with various

clayey materials (Gkouma et al., 2022; Fig. 10).

The aim of this method is not to create a single rigid and authoritative view of the site, but to create a framework for testing different possible interpretations that can evolve throughout the development of the excavations and studies at Dhaskalio, thereby giving future researchers the opportunity to understand and refine its built environment. For example, users have the ability to interact in three dimensions with all available specialist data. This can be queried to display data divided into each of the three phases of the site (Phase A, B and C), which can then be viewed and analysed within the corresponding phase of architecture. In short, it allows specialists to project themselves into and experience the former built environment of the settlement. Not only does it enhance their understanding of the effects of proposed interpretations, but it also provides a shared experience for a large team of people, who can then examine their analytical results within this context and build a wider, more accurate interpretation. From there, they can more easily construct a common interpretative model of the excavation and site.

3. Results

The data produced by this approach provide new ways of engaging with intra-site archival content. Through the incorporation of the earlier excavation data into the 3D GIS we have been able to reconstruct partially excavated structures and join together surfaces excavated between different seasons. A primary aim of this system has been to make something interactive and thus encourage the user to explore data together that would otherwise have been difficult to visualize in the same space. This has been aided greatly by the use of visual architectural reconstructions. Combining the special find artefact, stratigraphic data, and architectural reconstructions allows one to consider spaces in their entirety, even when such structures were excavated using varied methodologies and a decade apart. Two case studies in particular illustrate the value of this methodology. The first concerns Building A, which was excavated in two different trenches, ten years apart, during two separate seasons and using two different recording methodologies. The second concerns Building Γ, excavated during the 2016–2018 seasons, which underwent three distinct phases associated with various activities.

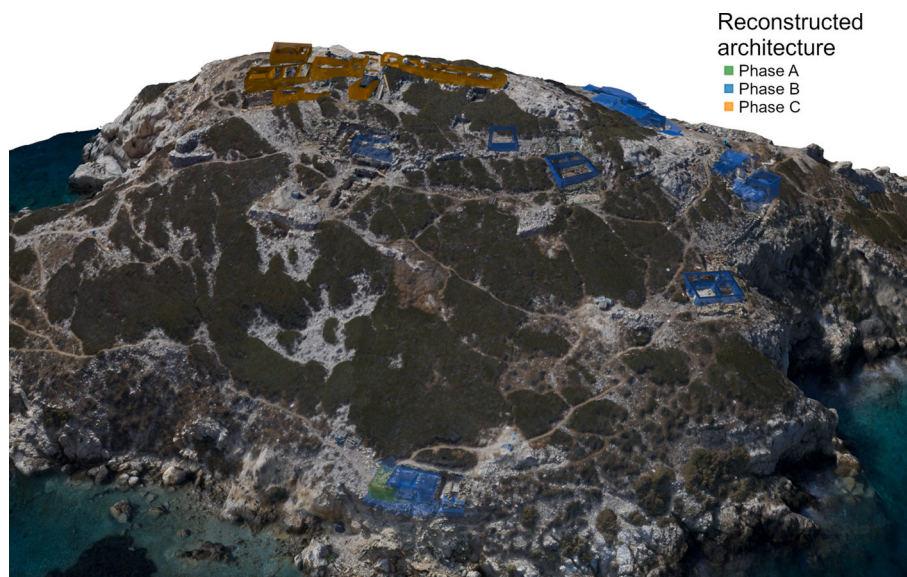


Fig. 9. Partial 3D reconstructions of the site's excavated architecture, coloured by phase (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

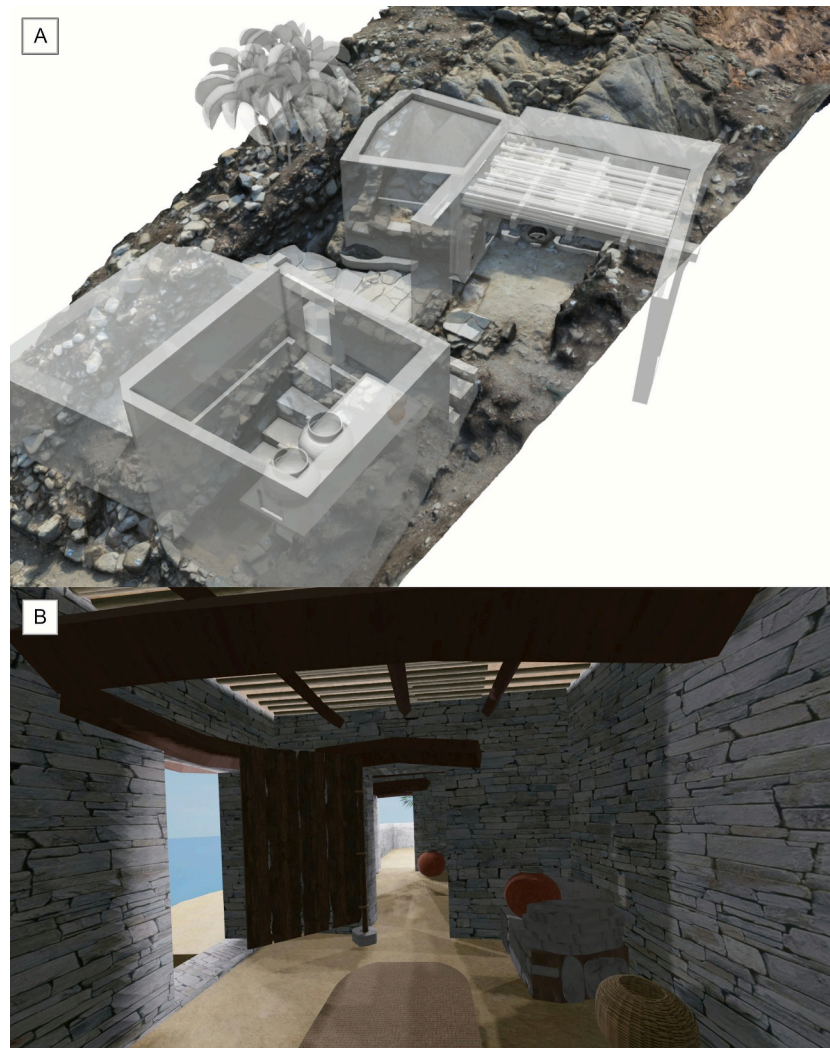


Fig. 10. 3D reconstruction of the architecture of Trench B (a), highlighting building materials with semi-transparent architecture in the GIS environment. Inside Building Γ phase 3, Trench H (b), with stylised rendering, showing architectural elements (screenshots from ArcGIS Pro and Blender, illustration by R. Campbell and M. Floquet, the Keros Project).

3.1. Building A

Building A, located at the summit of Dhaskalio, was first excavated during the 2007 season. Only the northern half of the building was explored via Trench VII, which revealed two elongated rooms linked by a doorway. A second door, leading to a room in the south, suggested that the building continued outside of the limit of Trench VII, which was confirmed by a small trial trench to the south. The remainder of the building was investigated through the opening of a new trench in 2016 and 2017, Trench F, which exposed the rest of the structure, which had been built on a terrace providing a level platform for the construction. Composed of five rooms in its latest construction stage, it presented a rectangular shape with a slightly curvilinear north-west corner (Fig. 11). It was accessible from a bordering alley to the south-west, by a narrow door leading to the central room that accessed the other spaces. The methodology presented in this paper has made it possible to merge the different types of recording of this single building allowing us to have an overall view and understand its morphology, use, and phasing, connecting surfaces between the two rooms. More specifically, by means of this approach, we were able to identify a stage of reconstruction, during which the entrance of the building, originally in the north, was displaced to the west. This significant modification would have been much more difficult to detect using a traditional recording system.

Moreover, this methodology not only allows us to gather disparate architectural information from distant excavation campaigns but also enables us to group and visualise floor surfaces and artefacts from the same context, despite being excavated several years apart. As an example, layer 37 from Trench VII and context 66 of Trench F, excavated respectively in 2007 and 2017 and making up two parts of the same surface, can be visualised together in the 3D GIS (Fig. 12, the latter with artefacts left in situ). The corresponding digitised points, shown as icons that represent their find type, represent where the level was taken for each object in 2008. In a comparison with the 3D reconstruction of the layer using retrospective photogrammetry, the heights match up and the position is satisfactorily accurate – between 5 mm and 8 cm (the larger difference certainly being related to field error in measurement via the dumpy level and baseline offset). This approach enables project specialists to understand the connections between floor materials excavated years apart more easily, facilitating the identification of dispersed assemblages of finds across two different trenches (particularly fragments of broken pots). This overall approach has allowed this building to be viewed in its entirety for the first time since the Early Bronze Age.

3.2. Two architectural phases of building Γ

In the case of Building Γ, which was excavated during the 2016 to

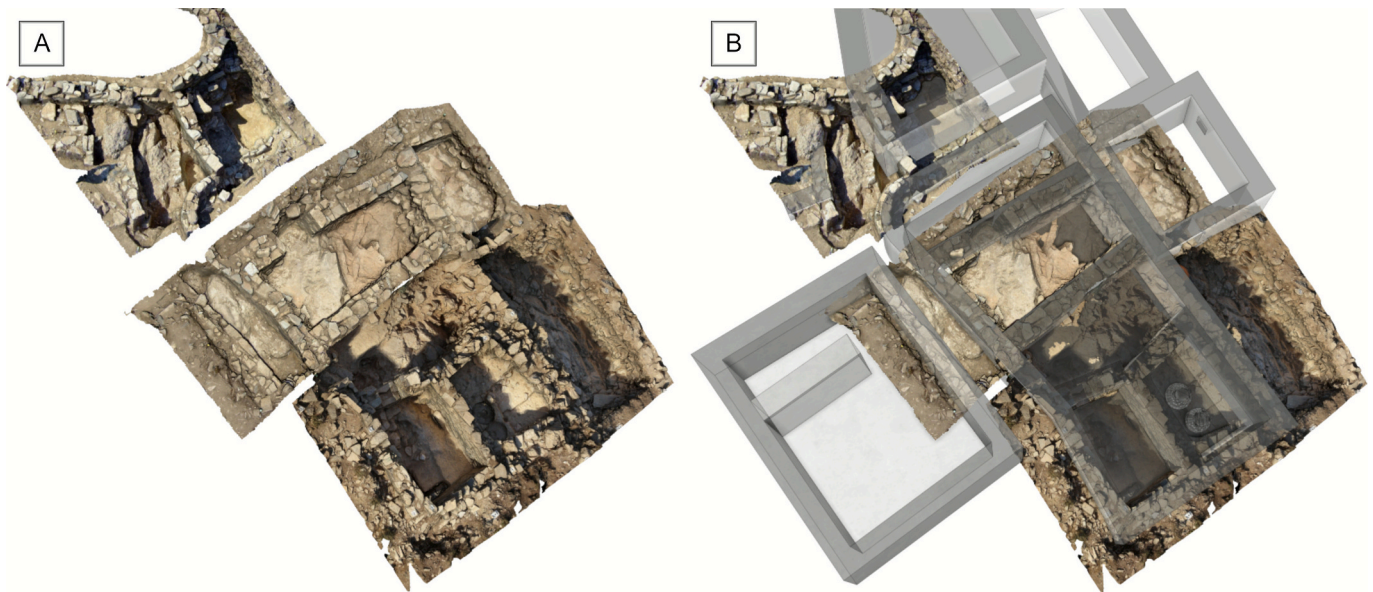


Fig. 11. (a) Photogrammetric models from Trench VII and Trench F (b) Building A architectural reconstruction (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).



Fig. 12. Building A showing a doorway between two rooms with equal floor surface, from the two seasons – Trench F, context 66 (left) and Trench VII, layer 37 (right; screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

2018 season in Trench H, the recording methodology enabled us to produce a phased, comprehensive documentation that includes photogrammetric models, artefacts, and a phase-by-phase 3D architectural reconstruction. Three distinct phases of construction and occupation, spanning several centuries, have been identified.

The first phase, associated with the site's ceramic Phase A (EC IIA), consists of a building complex where only two spaces have been identified thus far (Fig. 13a). To the north, a trapezoidal area, thought to

serve as an exterior courtyard, seems to have been used for extensive metallurgical activities. In the centre of this space, two circular hearths dedicated to copper metallurgy have been identified, along with numerous metallurgical artefacts. This courtyard leads south to a room, which may have been roofed, accessible through a large, centrally located doorway. A pivot found in the corner of the threshold suggests that the door was secured with a wooden door panel. Two additional possible hearth features were discovered in this second room, suggesting

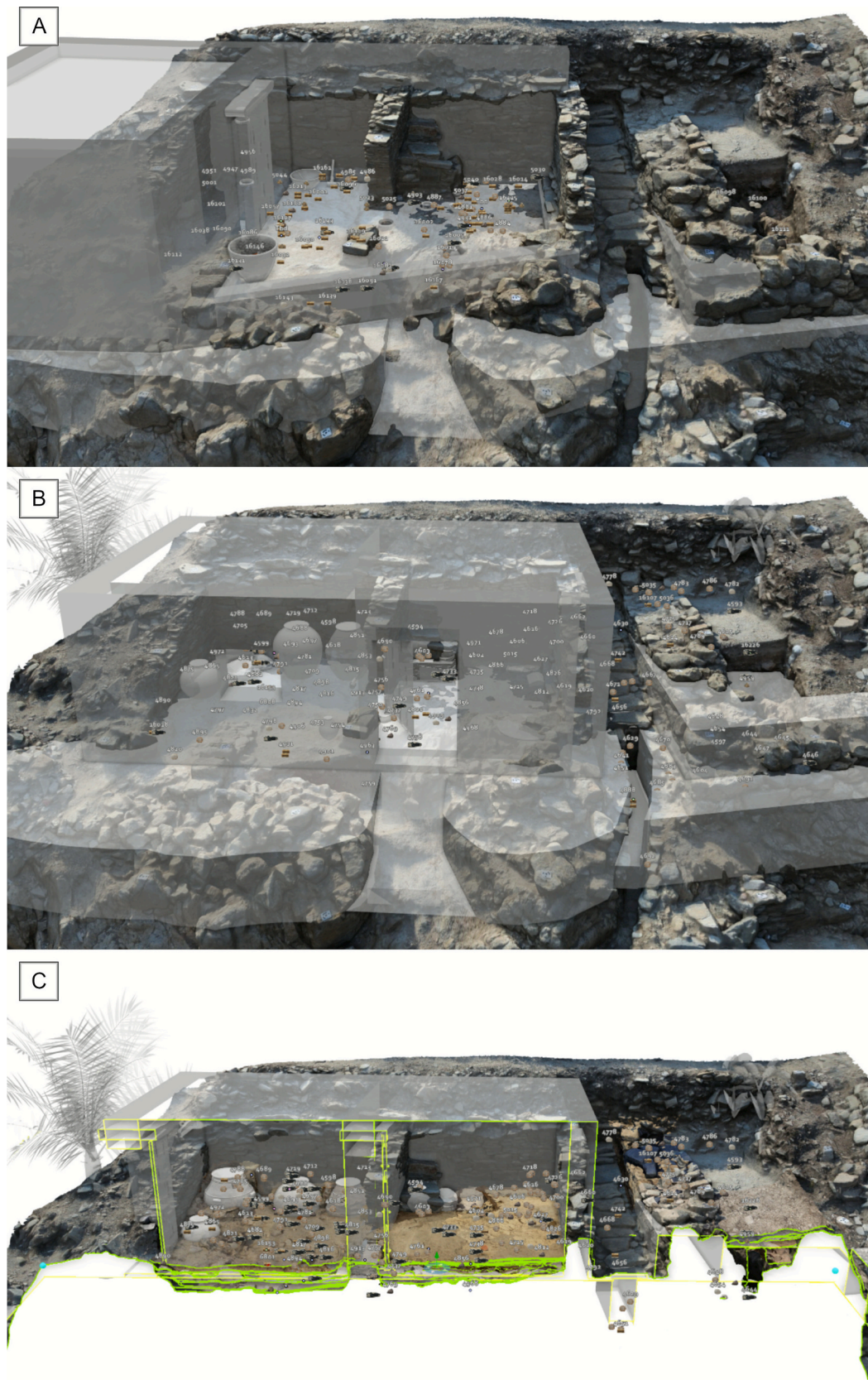


Fig. 13. GIS interface showing two phases of Building Γ with architectural reconstructions, showing architectural Phase 1 (a), Phase 3 (b) and section of Phase 3 (c). Each shows artefacts and contexts related to the corresponding phase only, with section created using the 'Slice' tool (screenshot from ArcGIS Pro, illustration by R. Campbell, the Keros Project).

that the whole building might have been constructed and used specifically as a metallurgical workshop.

The building's second phase included several spatial modifications with no clear architectural definition, and it appears to have retained its artisanal function. During this phase, only a single, unified space has been identified. A small, purpose-built metallurgical hearth was constructed against the western wall, while a substantial deposit of metallurgical tools, including a stone mould, found in the southwest corner of the room, probably relates to this phase.

Finally, during the third phase, the building entirely changed function. The single space of the second phase was divided by a partitioning wall into two rooms of equal size (Fig. 13b). The two rooms were linked by a centred door which was originally barred by a door panel. The room to the north seems to have been at least partly used for the production of pigments, as attested by the presence of a palette and a grinding stone, both in steatite, carefully placed against a shelf in the south-west corner of the room. Meanwhile, the room to the south was seemingly used as a storage space. Three large pithoi were aligned and slightly embedded in the earthen floor, against the western wall of the room, while the sherds of a broken globular jar were found on the floor. A possible third space in the south was accessible by a door placed in the southeast corner of the room. Once again, the pivot found in the corner of the threshold indicates that it was barred by a door panel. During this third phase, it seems that the building could be entered by a door in the eastern wall of the northern room.

Tying specialist and artefact data, ceramic phasing information, deposits, and surfaces together with the interpreted architectural context enables the exploratory analyses of all data recorded within Phase 3 of the building in one interface (Fig. 13c).

Slicing the models in section (using tools inbuilt to ArcGIS Pro), offers a deeper examination of the various phases and floors – as well as the artefacts associated with them – that make up each architectural phase. This multi-phase reconstruction of the building offers project specialists a comprehensive perspective of the finds and samples they are analysing, enhancing their understanding of the use of space.

4. Discussion

This paper aims to highlight the benefits of bringing together data collected a decade apart in a unified GIS intra-site 3D archive. The system contributes significantly to the role of reflexivity in the Keros Project's excavation and interpretation practices. It presents a better comprehension of the site overall, especially from an architectural perspective, where buildings and architectural remains are able to be seen in-situ, albeit digitally, together for the first time.

4.1. Practical challenges and time costs

One of the primary challenges lies in the time-consuming process of integrating old special find and specialist data, and especially excavation layers. Moreover, handwritten field notes from earlier excavation seasons often require extensive decoding due to issues such as illegible handwriting, miswritten numbers, or omitted levels. Many of these errors only become apparent when attempting to visualize the data in 3D. While elevation data often plays a secondary role in standard 2D GIS systems so long as the X and Y values are consistent with expectations, the importance of height values is magnified in a 3D environment, revealing discrepancies that were previously overlooked.

Digital and analogue legacy data have not always been organised and stored to archival standards. Missing metadata and finding aids add considerably to the workload of incorporating older datasets. Once done, however, contextual metadata can be exported to standard archive formats to be stored with the data in the future.

Overall, implementing such a comprehensive system, while yielding significant payoffs, inherently involves substantial investments in time, resources, and patience. The initial setup proved time-consuming, a

challenge exacerbated by the ad hoc development. With clear and well structured workflows, however, subsequent time overhead in the field is drastically reduced. With all historical datasets being different in terms of size, quality and content, concrete estimations of work effort to incorporate legacy data is not possible. As discussed elsewhere (Campbell et al., 2024), resource constraints such as technical equipment, proprietary software, and a significant knowledge threshold, are further critical considerations.

Extensive 3D reconstruction has not reduced (and was never meant to reduce) the time spent recording in the field, but with the improved data quality and added options for analysis and visualisation, post excavation work can progress faster and more systematically.

4.2. Reconciling excavation practices

Methodological and technical changes in the excavation practices create challenges for data compatibility and comparability. The paperless 2016–18 excavation seasons produced different and far richer data than was possible in the 2007–8 seasons. Earlier iterations of the 3D GIS system were constrained to born-digital data from the 2016–2018 seasons, along with 2D and 2.5D representations of trench boundaries and architecture from 2007 to 2008. While these depictions were useful, they failed to fully capture the complexity of stratigraphy and architecture, particularly at the summit of the site. Determining precise spatial relationships within and across these areas has been a key success of this 3D archive, which allows for a complete 3D view for all excavation trenches, aiding the archive's capacity for comprehensive spatial and visual analyses.

4.3. Retrospective photogrammetry

Retrospective photogrammetry, of stratigraphic layers in particular, relies on manual insertion of GCPs during post-processing, and often needs several iterations of camera alignment and model creation. On occasion, models proved unfeasible, and thus reliance on 3D polygons was necessary. Overall, only 15 % of retrospective photogrammetry from the 2006–8 seasons failed. Additionally, the resolution and quality of the generated 3D models vary considerably. Models based on a limited number of field photographs—sometimes as few as three or four—lack the detail and precision of models derived from the more comprehensive photographic datasets of later seasons. Models from the earlier seasons frequently suffer from poor texture and inadequate differentiation of angles needed for effective photogrammetry. Nonetheless, the resulting 3D surfaces often remain more accurate than hand-drawn polygons, even if they lack precision. Incorporating such models, despite their limitations, ensures the comprehensive integration of all geospatial elements into the archive, which is invaluable for contextualizing the excavation data. The results from using analogue photographs presented by Wallace (2017) and Unhammer et al. (2024) shows the potential of working directly with high quality negatives or slides over the first generations of digital imagery. However, due to the cost of analogue photography, the likelihood that enough pictures were captured for effective context-level photogrammetry is far lower in pre-digital projects.

4.4. Long-term data preservation and accessibility

While the current work has focused on the creation and use of a central archive during the lifetime of the Keros excavation projects, the project is conscious of the challenges associated with long-term preservation of digital data in new and varied data type. 3D data and high-resolution photogrammetric image-sets consume large amounts of storage, and would be prohibitively expensive to archive en masse with currently available research repositories. The collation of information from disparate analogue and digital data carriers into a central framework, standardisation of types and terminology, and a focus on free and

open formats, however, means the CIF facilitates future archiving efforts.

With a single source of information, the development of new platforms for interaction with some or all aspects of the data has been drastically simplified. Efforts are underway to provide a web-based interface to the full dataset, albeit behind access restrictions (see [section 4.5](#) below; [Indgjerd, 2025](#)).

4.5. Future directions and considerations

The paperless recording in 2016–18 already went beyond being a skeuomorph of analogue systems (as discussed by [Taylor and Dell'Unto, 2021](#)), and shaped the way people worked both during the excavations and after. The unification of all previous excavation data in a spatially aware field recording system ready to be brought into the field for the next campaign at Dhaskalio is a step towards a further transformation of these practices. Now, long-gone layers and covered up walls of neighbouring areas are readily available for the archaeologists on-site, contextualising the ongoing excavation in situ.

A goal for the next iteration of field work is the development of an automated pipeline for immediate creation and visualisation of 3D models during excavation, making 3D documentation a fully integrated part of the reflexive practices which support recording, interpretation and decision making in the field (fulfilling the goal of 3D 'at the trowel's edge' as formulated at Çatalhöyük a decade ago; [Berggren et al., 2015](#)). While the full-featured ArcGIS Pro project currently remains restricted to computer access in the lab, integration of individual models in the field recording platform using the open source 3DHOP JavaScript library will give access in the field the moment a model is processed ([Indgjerd, 2025](#); [Potenziani et al., 2015](#)).

The move from a VR 3D-GIS into a Mixed Reality (MR), as showcased for archaeological field data by [Dilena and Soressi \(2020\)](#), would further break down the barrier between digital data and the reality in the field. The projection of earlier trenches, strata, finds, or geochemical data onto the ongoing excavation site in real-time would be an important aid in the field decision-making process. Our dataset and recording workflow is well suited to taking advantage of MR tools. There are, however, still technological limitations to the implementation of an MR application at the scale required for the excavations on Dhaskalio.

In parallel with this, work has started on the incorporation of survey data recorded for the Keros Island survey (2012–2013), Southeast Naxos survey (2015), and Kato Kouphonisi survey (2018) into the system. This forms not only legacy data, recorded in various stages of digital integration, but data recording different temporal, spatial and theoretical scopes. It is our hope that this will better contextualise the excavation within the wider landscape, and allow seamless movement between the different scales. The extensive survey data is redefining the understanding of Dhaskalio and the site's subsistence basis, and interoperability of these datasets will be key to improving the understanding of this *taskscape* ([Margaritis et al., 2024, 128–131](#)).

Finally, regardless of its capacity to be used to produce photogrammetric models, records from earlier projects on Keros, such as the 1980s campaign, should be digitised and made available to the highest level of spatial data possible.

5. Conclusion

Maintaining a dialogue on best practices for the long-term single project archives is crucial in a period of increasingly born digital data production. Otherwise, we are at risk of losing the richness and importance of older project archives, simply because they are not as shareable or easy to work with as their born digital counterparts. The successful 3D modelling of structures and contexts excavated almost twenty years ago underscores the importance of data retention and archiving. Technological developments are hard to predict, and recorded data may be useful in unforeseen ways. This programme has demonstrated the

benefits of integrating data collected a decade or more apart into a unified 3D intra-site GIS archive. The system offers significant benefits to reflexivity in archaeological practices, providing a more holistic understanding of the site – particularly in its architectural features – by enabling the digital visualisation of stratigraphic relationships across excavation trenches. For the first time, buildings and architectural remains can be examined together as a whole. Practical obstacles, such as the labour-intensive digitisation of field notes and retrospective photogrammetry, and reconciliation of excavation practices across seasons with differing methodologies, highlight the complexities of integrating archival and analogue data. Despite such issues, incorporating these elements into the 3D archive ensures a more comprehensive spatial and visual analysis, enabling a richer interpretation of the site's stratigraphy and architecture.

CRediT authorship contribution statement

Rosie Campbell: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marie Floquet:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Hallvard R Indgjerd:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Michael J Boyd:** Writing – review & editing, Writing – original draft, Validation, Project administration, Funding acquisition. **Colin Renfrew:** Supervision, Project administration.

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Data availability

The authors do not have permission to share data.

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