

**AN INTEGRATED ‘LIVING’ 3D
DATABASE USING
PHOTOGRAMMETRY AND GIS:
Trenches B and H from Early Bronze
Age Dhaskalio, Greece**

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Archaeology

Front page figure: Dhaskalio photogrammetric model with polyline walls in the 3D GIS workspace (figure by author).

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ACKNOWLEDGEMENTS.....	5
1 INTRODUCTION.....	6
1.1 FROM GIS TO 3D GIS	7
1.2 PHOTOGRAMMETRY IN ARCHAEOLOGY	9
1.3 RELATED RESEARCH – PRACTICAL USES OF IMAGE-BASED MODELS AND 3D GIS	12
1.3.1 <i>Recent Developments of 3D GIS and Site Recording in Archaeology</i>	13
1.3.2 <i>Current Issues and Missing Pieces</i>	17
1.4 DHASKALIO-KEROS, GREECE.....	19
1.5 RESEARCH OBJECTIVES AND QUESTIONS	22
1.6 THESIS STRUCTURE.....	23
2 3D GIS AND DATA ACCESSIBILITY.....	25
2.1 WHAT IS 3D GIS?	25
2.1.1 <i>Software Development</i>	26
2.2 FOSS, DATA ACCESSIBILITY AND SUSTAINABILITY	27
2.2.1 <i>Software Selection: Open-Source vs Proprietary Software</i>	27
2.2.2 <i>Storing and Sharing Data into the Future</i>	29
3 THE EARLY BRONZE AGE SITE OF DHASKALIO, GREECE	31
3.1 KEROS: KAVOS AND DHASKALIO.....	31
3.2 PREVIOUS RESEARCH.....	33
3.3 OVERVIEW OF TRENCHES.....	34
3.3.1 <i>Trench B</i>	35
3.3.2 <i>Trench H</i>	38
4 DATA ACQUISITION AND METHODOLOGY	40
4.1 INTRODUCTION, FOCUS AND OBJECTIVES	40
4.2 DHASKALIO DOCUMENTATION METHODS AND DATA ACQUISITION.....	40
4.2.1 <i>The Dhaskalio Dataset</i>	41
4.2.2 <i>The Photogrammetry</i>	42
4.2.3 <i>SQL Databases: SQLite vs Postgres</i>	44
4.2.4 <i>Photographs, Literature, and Other Files</i>	46
4.3 SOFTWARE	47
4.4 WORKFLOW	48
4.4.1 <i>Setting Up the Local Scene</i>	50
4.4.2 <i>Importing Files</i>	52
4.4.3 <i>Joining Data</i>	53
4.4.4 <i>Adding Attachments</i>	54
4.4.5 <i>Configuring Pop-Ups</i>	56
4.4.6 <i>Symbology and Time</i>	57

4.5	REBUILDING THE WORKFLOW IN OTHER SOFTWARE.....	59
5	RESULTING PRACTICAL APPLICATIONS	60
5.1	TRENCH DATA AND VISUAL ANALYSES.....	61
5.1.1	<i>Integration of Site Data</i>	61
5.1.2	<i>3D Files and Components</i>	64
5.1.3	<i>Volumetric Data</i>	71
5.1.4	<i>Exploring Time</i>	72
5.2	STATISTICAL ANALYSIS AND CASE-STUDY.....	73
5.2.1	<i>The Density-Based Clustering Tool</i>	74
5.2.2	<i>Clusters in Special Find Artefacts</i>	75
5.2.3	<i>Single Strata Analysis</i>	79
5.2.4	<i>Metallurgical Finds</i>	82
5.2.5	<i>Clarifying Distribution Patterns and Trench Taphonomy</i>	84
5.3	CHAPTER CONCLUSION.....	86
6	DISCUSSION	87
6.1	WORKFLOW OVERVIEW.....	87
6.2	NATURE OF THE DATA.....	88
6.3	DATA ACCESSIBILITY AND SUSTAINABILITY.....	90
6.4	OTHER METHODOLOGIES.....	91
7	CONCLUDING REMARKS.....	96
	ABSTRACT.....	99
	INTERNET RESOURCES	100
	BIBLIOGRAPHY	101
	LIST OF FIGURES	108
	LIST OF TABLES	112
	SUPPLEMENTARY MATERIAL.....	113

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1 INTRODUCTION

Archaeologists have long appreciated the irony within our discipline that in order to understand the past, we must often actively destroy its remains. It is for this reason that excavation records are vital for future studies. In recent years, technological advancements and newly employed methods such as image-based 3D modelling have begun to challenge this notion (Roosevelt et al., 2015). While modelling techniques such as structure-from-motion photogrammetry are becoming more and more common in archaeological practices, rarely has it been used for more than visualisation purposes or to support the process of manual field drawings (Magnani et al., 2020). It is important to move past the phase of record keeping and visualisation, toward that of significant interpretative value. The improved capacity of computer specifications, normalisation of photogrammetric and 3D modelling as means of archaeological recording, and the increased capacities of current 3D GIS software, have created an ideal environment to develop and expand the use of the third dimension in archaeological analysis.

This project aims to use 3D modelling in a comprehensive and meaningful way to be used at an interpretive level. Data from the Early Bronze Age (EBA) site of Dhaskalio, Greece, excavated in the 2016 - 2018 field seasons is the basis of this project. A brief outline of the site can be found in section 1.4, and more extensive discussion of its recording methodologies can be found in chapter 3.

In this thesis I will propose a workflow for creating a 3D GIS environment that incorporates all site data in synthesis with image-based 3D models of each stratigraphic context and structure excavated at the site. This is to be used as an interface for running comparative queries across the trenches and aiding site interpretation by way of spatial analysis. Furthermore, it will act as an interactive database, where site data, photographs, and specialist data and interpretations can be accessed in a single environment.

1.1 FROM GIS TO 3D GIS

Modern archaeologists are no strangers to Geographical Information Systems (GIS). First developed in the 1960s to analyse spatial and geographic data, along with Computer-Aided Design (CAD) software, it became an increasingly common tool for visualising and analysing archaeological data by the 1980s (Kvamme, 1999). While CAD allowed vector drawing and cartographic tools which are useful in fieldwork for site and architectural recording, it was not intended to be used as a mapping tool and thus lacked support for geographic tools. Meanwhile, GIS included the ability to draw vectors, but, as the name implies, was also intended to be used for geographic and mapping capabilities, allowing documents to be scanned and georeferenced (Jensen, 2018a). Furthermore, unlike CAD, GIS has embedded database capabilities allowing associated documents, images, and geographic data to be stored together. Abdul-Rahman and Pilouk (2008, 1) note that the fundamental difference between GIS and CAD is the handling of spatial attributes.

Users have since embraced the expanding set of complex spatial analysis tools available in GIS to run queries and generate new data from pre-existing datasets, such as satellite imagery, maps, and photographs, and the representation of spatial data such as site locations, mapping, and artefact locations and the relationships between them. However, traditional GIS functions in a 2D environment, while archaeological data is profoundly 3D in nature. Attempting to represent real-world data in a 2D environment, limited by the use of only x and y coordinates has been a well-known problem in archaeological applications of GIS (Ebert, 2004; Fletcher & Winter, 2008; Forte et al., 2015; Klinkenberg, 2016; Dell'Unto et al., 2017; Richards-Rissetto, 2017; Richards-Rissetto & von Schwerin, 2017). The inability to represent two overlapping points with different elevations is perhaps the most problematic issue in traditional GIS, making the representation and analysis of some spatial relationships impossible. The use of the third dimension, the z

coordinate, has been a major development to GIS technologies and is most commonly represented in Digital Elevation Models (DEMs).

DEMs have been used in conjunction with orthomosaics to create '2.5D', which extrudes objects as pixels based on their elevation. However this method creates a schematic object limited to pixel size, and so is unsuitable for vertical elements or models that require higher details (Richards-Rissetto, 2017). Fig. 1.1 shows an example of a DEM and the related orthomosaic used to create a 2.5D model. The need for true 3D in GIS software is evident and has been in development particularly over the past two decades, influenced by the increasing availability of computing power, and the advancement of largely automated workflows to generate detailed data.

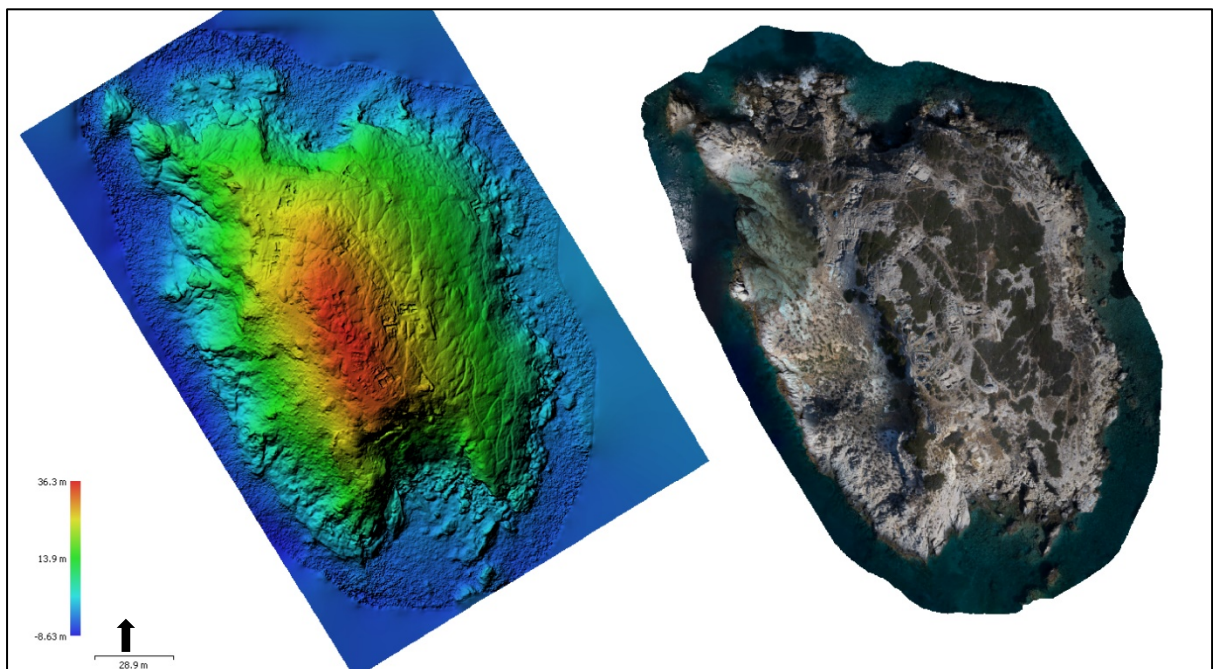


Figure 1-1 Examples of DEM (left) and orthomosaic (right) of Dhaskalio (by author)

A true 3D GIS system should encapsulate all of the abilities of traditional GIS, that is for data entry, database management, data analysis and manipulation (Wheatley & Gillings, 2002). While various forms of 3D GIS has been available for some time, it has only emerged in archaeological research in more recent years as the technology has improved and become more financially accessible (for example, see Balletti et al. 2015; Dell'Unto et al. 2017; Opitz & Nowlin 2012; Richards-Rissetto 2017; van Leusen & van Gessel 2016). While several well

known, free GIS software such as QGIS and GrassGIS support the use of 2.5D, unfortunately, high quality true 3D GIS is not yet available outside of proprietary software, with the main software being ESRI's ArcGIS ArcScene and ArcGIS Pro. This issue will be discussed in more detail in relation to the current thesis's methodology in the following chapter.

1.2 PHOTOGRAMMETRY IN ARCHAEOLOGY

In 1838, the stereoscope was introduced by Sir Charles Wheatson, using overlapping drawings to create a 3D effect. Upon the introduction of photography, the same optical concepts were applied to overlapping photographs in the mid-1800s by researchers such as Albrecht Meydenbauer and Aime Laussedat for use in civil engineering and recording (Fussell, 1982). In 1885 Persepolis became the first archaeological site recorded by means of photogrammetry (Lužanin & Puškarević, 2015). In this period, photogrammetry was in its infancy, referring to 'stereo photography', the use of two overlapping photographs taken of a single scene and then viewed through a binocular eyepiece to create a three-dimensional effect, allowing accurate measurements to be taken (Fussell, 1982; Albertz, 2007). By the 1960s, the Harvard-Cornell Archaeological Expedition to Sardis had begun experimenting with early forms of photogrammetry for site recording and taking precise measurements (Whittlesey 1966). In 1982, Anderson (Anderson, 1982) predicted the adoption of measurement photogrammetry by archaeologists as a replacement for traditional surveying methods once the financial burden of hardware was lowered. Modern photogrammetry saw its expansion during the mid-nineteen-eighties due to the rapid development of computing power and software

design. In the years since, photogrammetry has evolved immensely and become a digital tool, and it would appear Anderson’s prediction has been proven true.

Modern references to photogrammetry typically mean ‘structure from motion’ (SfM), which is a more recent development that has greatly contributed to the expansion of digital photogrammetry software packages (Douglass et al., 2015). SfM works by the determination of the spatial and geometric relationship of a target (in this case, archaeological remains or an artefact), through the movement of a camera (fig. 1.2), which is then processed into a three-dimensional mesh using complex computing algorithms (Moulon et al., 2012).¹ Currently, software programs, such as Agisoft Metashape and Reality Capture, automate the process of creating image-based 3D models from overlapping photographs taken with UAVs or terrestrial cameras. Georeferencing photogrammetry using GPS, DGPS, and Total Stations has resulted in quantitatively precise measurements for a low cost.

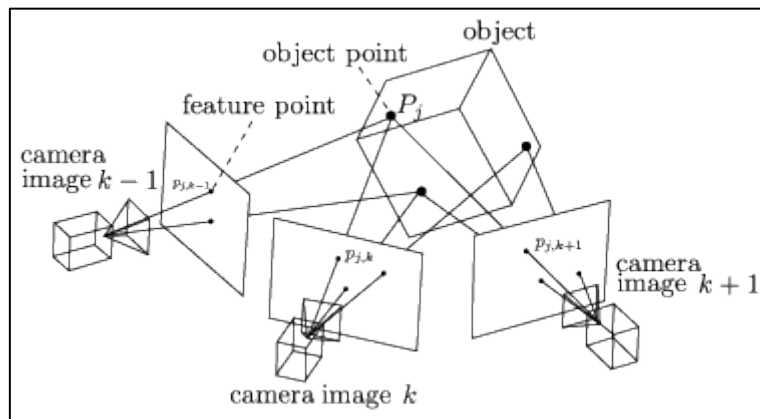


Figure 1-2 Diagram demonstrating the process of reconstructing an object using structure from motion (from Moulon, Monasse, and Marlet 2012, fig. 2)

¹ For simplicity, from this point, the term ‘photogrammetry’ and ‘photogrammetric models’ will be used in to refer to structure from motion photogrammetry and 3D models.

These can be used for a variety of purposes from landscape mapping to the high-resolution recording of burials as seen in fig. 1.3.

Currently, photogrammetry as an archaeological tool appears to be in its second phase of development. Software and image capture have become more accessible. While efforts to update archaeological field recording strategies by the use of 3D tools have a long history, it is only with current technology updates and low-cost methods that have seen it become commonplace in fieldwork and labs



Figure 1-3 Demonstrating high-resolution photogrammetry and precise measurements. 3D reconstruction of a Mycenaean child burial at Khirra, Greece. Created using Agisoft Metashape (by author).

alike. For example, orthorectified photos, images created by photogrammetry which take the lens distortion out of an image set to create a single planar photo, are popular alternatives to manual field drawing of site architecture (Dell'Unto et al., 2017). A significant article by Roosevelt et al. (2015) discusses the use of an entirely digital recording system for excavation, with emphasis on recording three-dimensional data by use of photogrammetry.

Perhaps the most inherent issue to modern archaeologists in the use of photogrammetry is the limited number of standard procedures in fieldwork and in publishing. More recently an effort has been made by some to encourage better field practices for photogrammetric implementation, such as by Sapirstein and Murray (2017), who advocate for more comprehensive project planning and a thought-out selection of equipment and trained personnel. Basic principles for publishing and

archiving 3D data have not yet been fully developed (though several have been suggested, such as Reinhard 2015; Richards-Rissetto and von Schwerin 2017; Pilzecker 2020). This issue will be discussed in further detail in Chapter 3's sub-chapter on open science and data accessibility.

In sum, photogrammetry as a method of archaeological recording has become a common practice for many projects. The ability to access highly detailed, geometrically precise three-dimensional models of an excavation as well as orthorectified images and DEMs by what has become a predominantly automated and accessible system is certainly to the benefit of archaeologists. The final purpose and particular uses of these models have been a discussion point for many (Douglass et al., 2015; Olson & Caraher, 2015; Kuroczyński et al., 2016; Waagen, 2019). The integration of image-based models within recording systems aiming to use photogrammetry for database visualisation and analytical functionality will be further discussed in section 1.3 below.

1.3 RELATED RESEARCH – PRACTICAL USES OF IMAGE-BASED MODELS AND 3D GIS

The application of spatial technology in archaeology is typically classified into three categories: visualisation, data management, and spatial analysis (Ebert, 2004; McCoy & Ladefoged, 2009). The use of GIS as a 'living document' was discussed in 2009 by Gonzalez-Tennant (2009) for the Otago Goldfields in New Zealand. Gonzalez-Tennant stressed the need for archaeologists to learn to organise their GIS systems in a more structured manner that would allow for the easy dissemination of site data. Their concern for organisation and their example of using GIS as a site-wide 'living document' have become staples of several current methods to 3D GIS. The initial two classifications of GIS as a visualisation and data management tool are well represented in the use of image-based 3D models in archaeology, however, there is an underrepresentation for their use as a technique for spatial analyses.

This brief review will discuss both desktop and web-based systems for representing 3D data. An advantage of web-based 3D database viewers such as the MayaCityBuilder (Richards-Rissetto, 2017), is that there is no dependency on software installation, and therefore encourages more interoperability between users. However, it relies on network speeds which can be a limiting factor, particularly if

the program is to be accessed in more remote regions, and especially problematic if the project is using a large number of high-resolution models each requiring rendering (Jensen, 2018a). Desktop software has its own benefits and pitfalls. While desktop applications such as ArcScene and ArcGIS Pro provide a more stable environment, they rely on the individual installation of software that is often proprietary, making data sharing more difficult.

The use of 3D models in a GIS environment by archaeologists has a short history. Much of this can be attributed to a technology-driven issue rather than theory driven. As previously mentioned, the adoption of robust 3D GIS is currently limited to specialised proprietary software. Nevertheless, there have been a number of recent studies exploring the potential workflows, uses, and theoretical frameworks of applying these digital documentation methods. Several of such studies will be discussed in short below.

1.3.1 Recent Developments of 3D GIS and Site Recording in Archaeology

The growth of digital archaeology has facilitated a widespread use of photogrammetry as a promising additional recording tool for archaeologists. It is considered an affordable and efficient way to produce photorealistic and geometrically accurate three-dimensional models of archaeological remains (Balletti et al., 2015; Dall'Asta et al., 2016; Jurda & Urbanova, 2016; Pierdicca et al., 2016). Even so, there have been frequent discussions on its purpose and the overall usefulness it has over manual recording. The potential of 3D modelling in the recording process of archaeology was discussed as early as the 1990s but not thoroughly addressed until the 2000s, by which time technological advancements in computing power and methodologies became more accessible. This survey of the current research landscape is by no means exhaustive, rather it aims to discuss some of the key developments to 3D GIS platforms, and the way in which projects are currently developing workflows and practical uses.

In recent years there have been several projects experimenting with 3D GIS as part of the site recording process. Forte and colleagues began a 3D-Digging project at Çatalhöyük in 2009, intending to digitally record and display the archaeological stratigraphy of a building (Building 89) and to demonstrate the relevance of 3D information for depositional and post-depositional activities (Forte

et al., 2015). This project has relied on a privatised specifically built program, TeleArch, to create a 3D GIS workspace, which support the integration of 3D files and spatial information (Kurillo & Forte, 2012). The focus of this publication was to demonstrate the visualisation aspects of the method such as viewing artefacts in situ and the ability to incorporate Virtual Reality (VR), rather than as a discussion on how 3D developments could be used more practically. More recently the project has further developed VR into their methodology by creating a VR app, Dig@IT, experimenting with public engagement and open-access for researchers to virtually explore the site's data (Lercari et al., 2018). The analytical uses for this so far do not stretch past basic measurements and the visualisation of three-dimensional data in tandem with the excavation database.

The Swedish Pompeii Insula V project (Dell'Unto et al., 2015) has used laser scans in tandem with select highly detailed photogrammetric models of the architectural remains of Insula V in Pompeii. Since the early 2000s the project has worked on incorporating 3D reconstructions and documentation methods into their methodology using laser scanning, and to a lesser degree, photogrammetry. The overall project aim is to investigate the domestic architecture in Insula V at Pompeii. The models have been put into ArcScene and connected to an exterior database (fig. 1.4). It has been used to generate new information on the relationships among the different structures present by use of 3D polygons and to classify the degradation

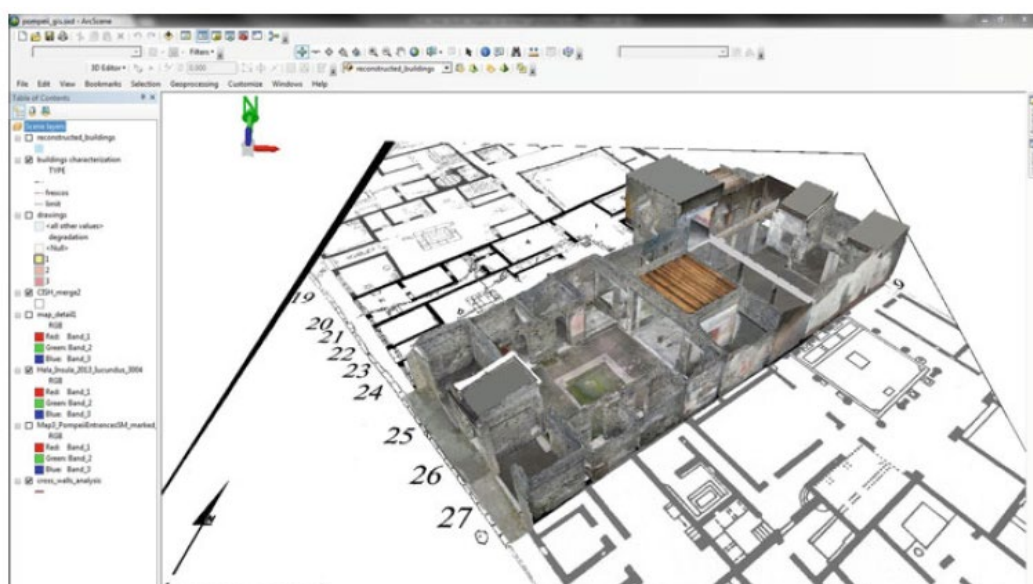


Figure 1-4 3D model of Caecilius Iucundus, insula V 1 at Pompeii in the ArcScene environment. (From Dell'Unto 2016, fig.5, 315.)

of wall frescos by use of the visibility analysis toolkits found within the software (Dell'Unto et al., 2015; Dell'Unto, 2016).

The development of WebGL and HTML5 to support web-based 3D environments has yielded archaeologists a more interoperable platform for developing and disseminating data. While companies such as Sketchfab are often used to share 3D data by the archaeological and heritage management communities, they do not provide the suite of tools to facilitate the complexity of customised data integration (Jensen, 2018a). However, several projects have begun developing web-based environments to fulfil the more complex needs of archaeological data representation. The MayaCityBuilder Project attempts to incorporate 3D models in a web-based GIS environment using 3D and 2D environmental and temporal data, with the objective to allow scholars to interact with the archaeology (Richards-Rissetto, 2017). The project uses segmented semantic 3D models to allow individual parts of the models to display individual annotations. VR has also been implemented in the project to emphasise the focus on interactivity between archaeological sites and their broader landscape, including archaeobotanical data and sounds. The long-term goal of the project is to create a procedural modelling repository of ancient Maya architecture allowing users to create georeferenced 3D buildings. However, at this stage, it appears that the project remains in the visualisation and data management facets of 3D GIS.

The work of Klinkenberg (2016) uses 3D models to represent every architectural element of the remains of a *dunnu*² feature at the Tell Sabi Abyad excavation, as well as models of each object found within. The project represents the excavation data in situ. It aims to be used not merely as a visualisation tool, but for the basis of spatial and stratigraphic analysis of the *dunnu*. The project is run through Esri's ArcGIS ArcMap and ArcScene software, incorporating excavation material and data with the 3D models for an environment where clicking a feature will result in the display of its associated background information (2016, 19). Unfortunately, only certain objects were taken as photogrammetric models, meaning some of the excavation data is inevitably lost or underrepresented within the model. While Klinkenberg does not use this system as an integrated 3D

² According to Klinkenberg, a *dunnu* is a type of settlement found in the Late Bronze Age Assyria.

database, it exemplifies the utilisation of 3D GIS as an analytical tool for the spatial analysis of relationships between artefacts, rooms use, and architectural elements.

A workflow incorporating photogrammetric models as part of the excavation recording process was tested by the Mesolithic site Kämpinge in south-western Sweden. The project captured photogrammetric models of several small trenches and incorporated them in a geodatabase using Esri's ArcGIS and ArcScene. The resulting database and low-resolution models were displayed on an iPad and used on site as a part of the recording strategy in real time (Dell'Unto et al., 2017). Overall, the project made use of the available technology to aid not only in the recording of trenches, artefacts, and architectural features, but as a method of reflexivity in excavation choices and to connect features which were not spatially related. The project also remarks that the use of volumetric TIN models could be used for stratigraphic analysis, although the specifics have not yet been published. The use of 3D GIS as a data management and visualisation tool is clear and Dell'Unto and colleagues observe that these aspects were some of the greatest benefits of the method, yet, again the capacity for more complex analyses has not been determined.

The Archaeo 3D-viewer demonstrates a compelling use of 3D GIS as a living, web-based platform, seen in fig. 1.5 (Jensen, 2018b). The system is designed to demonstrate a framework for interactive and fully integrated high-resolution 3D models with vector and textual data, and aims to deliver a platform suitable for collaborative research (Jensen, 2018a). It uses segmented photorealistic photogrammetric models of the excavation at Alken Enge in Denmark. Within the system, when any individual element is clicked on directly on the mesh, its documentation will automatically be provided. While this system itself is mainly orientated towards visualisation and display of excavation data and not the analysis of data itself, its creator does exemplify the use of 3D data to extend interpretative practices by combining rich 3D datasets with machine learning, using postholes as an example (Jensen 2018a, 159).

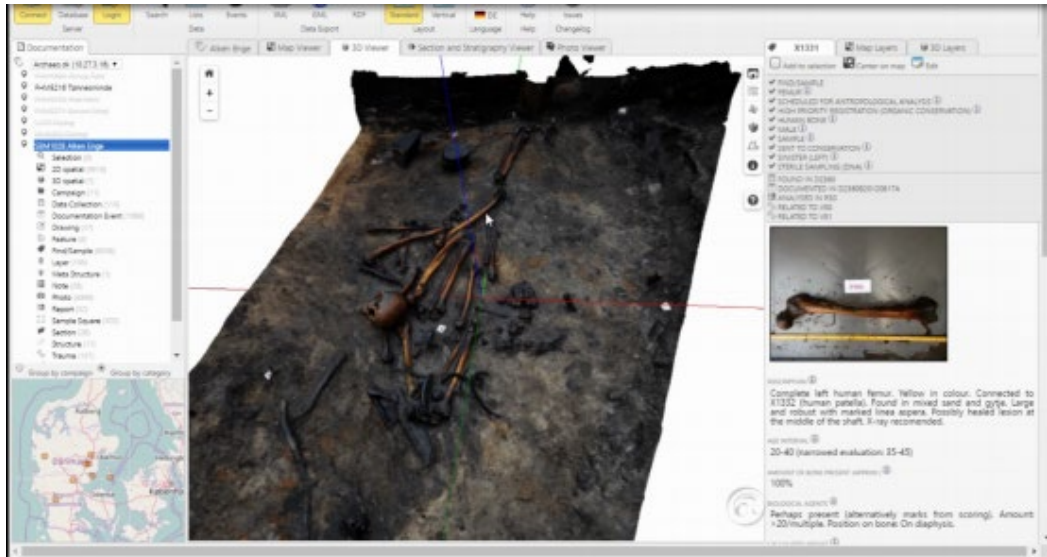


Figure 1-5 Screenshot from the Archaeo online database. (From Jensen 2018a Fig.4.7, 132)

The recent work from Gavryushkina (2018) proposed a workflow for digitising and visualising stratigraphic data in a three-dimensional environment by creating volumetric models of a trench in Chlorakas-Palloures, Cyprus. Rather than using photogrammetric models of the stratigraphy, the project used Total Station points and section drawings taken over the course of excavation to reconstruct the stratigraphy using volumetric TIN files in ArcScene. The project was able to use the volumetric models to analyse and find insights in the stratigraphic sequence of the trenches. While the 3D data within this project was linked to the excavation data, however, it was based on an external .csv file, meaning that editing the project in relation to the 3D data would not be possible from outside of the GIS.

1.3.2 Current Issues and Missing Pieces

It has been made clear by this brief survey of the practical and theoretical landscape that there are still considerable improvements to be made in the use of 3D GIS and the integration of image-based photogrammetric models into archaeology. A large factor of this is accessibility. Many software, such as ArcGIS, require expensive licences that limit their use. Open-science frameworks that necessitate the need for Free and Open Software (FOSS) and the ability to sustainably share and store data is an imperative issue within the current research. As chapter 2 will discuss, such paradigms still pose a problem at present for harnessing 3D GIS. Furthermore, many of the projects discussed above use custom-

built software and software extensions to compose integrated 3D GIS databases limited to internal use, such as at Çatalhöyük. This is highly problematic for most archaeological projects that lack of funding, time, or specialised skills that go into these solutions. The current research developments in archaeological 3D GIS are certainly immersive and impressive, however the workflows and software use are out of reach for most archaeological projects. Unfortunately, VR, for example, remains an expensive addition for most archaeological projects with its benefits yet to be established in analysis outside of the measures of innovation. Newhard (2015, 10) notes that the vast majority of applications of 3D modelling ‘still reside in the realm of display and presentation’, while those who do venture into more in depth analytical methods are few and far between. Furthermore, the large time investment required for what is often used simply as 3D visuals with few practical applications may be seen as a minimal return to the overall archaeological inquiry.

Moreover, many projects experimenting with photogrammetric modelling as a form of site recording often work with small or moderately sized trenches in relatively flat terrain (Waagen, 2019; Dell’Unto et al., 2017), or use daily overview models that would not be suitable to capture all of the excavated contexts in high-paced excavations. A true 3D GIS should ideally incorporate all elements of a traditional GIS, and this ought to include information for each stratigraphic unit. Of the above projects displaying 3D stratigraphy, few make use of photogrammetry to display photorealistic stratigraphy (Jensen, 2018a; Jensen, 2018b), and instead opt for using coloured 3D multipatch TIN layers to represent stratigraphy (Forte et al. 2012; 2015; Dell-Unto et al. 2017). While this method allows for easy identification of different stratigraphic layers, it significantly reduces the surface layer details of the strata.

This project envisages a move for image-based 3D recording from a passive means of recording and displaying representational data, to become an interpretative tool in consideration with the observation of Ebert (2004) and McCoy and Ladefoged (2009) that spatial technologies such as GIS should incorporate visualisation, data management, and spatial analysis tools. An outline of the site used as a case study for this project, Dhaskalio, will be discussed below in 1.4.

1.4 DHASKALIO-KEROS, GREECE

The small islet of Dhaskalio is located in the Small Cyclades in the Aegean Sea. In the Early Bronze Age (EBA) it was a part of a small promontory connected to the larger, now uninhabited, island of Keros. Although the islet of Dhaskalio was very briefly investigated in 1963 (Doumas, 2007), it was only following systematic excavations starting in 2007 by the Cambridge Keros



Figure 1-6 Keros and the Little Cyclades. Dhaskalio indicated by star (from <https://www.arch.cam.ac.uk/research/projects/current-projects/keros-project>, accessed 10, December 2020)

Project that it has been interpreted as an important regional centre in the EBA Aegean (Renfrew et al., 2007). In part this is due to its relationship overlooking the two ‘Special Deposits’ located at Kavos, on the adjacent beach on Keros, which has been made famous by the large amount of Cycladic Folded Arm Figurines looted from the site (Renfrew et al., 2009; Renfrew et al., 2007; Renfrew et al., 2012). Dhaskalio is recognised as a major settlement to the Early-Cycladic II Keros-Syros culture, and the largest currently known in the Cyclades (Renfrew et al. 2009). Analysis of fabrics from the ceramic assemblages shows that it has entirely been imported from other islands, such as talc-ware from Siphnos and volcanic-ware from Milos or Thera (Hilditch, 2013). The site may have functioned as a place of periodic habitation with little to no permanent occupation, but rather where the highly mobile maritime groups from the broader Aegean could pass through either to interact with one another, or to make ritual deposits of the Folded Arm Figurines at the adjacent site of Kavos (Renfrew et al., 2012; Broodbank, 2002).

The island is very small (approx. 1.75 ha on a flat plane), extremely steep, and provides very little in the way of habitability. Even so, the extensive remains of a

highly thought-out and planned 'settlement' have been uncovered here. The data I will be using comes from the site's second phase of excavation, taking place between 2016 - 2018. Part of the recording strategy of the site included an extensive photogrammetry program. While UAV was used for site-wide image-based models, DEMs and orthomosaics, the 3D models were mainly based on hand-held terrestrial cameras. Both intra-site and micro-level recordings were made of the architecture, stratigraphic units and layers, and other features, giving a three-dimensional representation of each taphonomic event. I will be using two trenches as case studies, Trench B and Trench H. Trench B is located on the northern side of the island while Trench H can be found in the north-eastern area of Dhaskalio. A more thorough discussion of the site, its excavation history, and the trenches can be found in Chapter 3, while details of the project's recording strategy specifications can be found in Chapter 4. While the 2016-2018 excavations opened eight trenches on the island, (A, B, C, E, F, H, L, and N), only the aforementioned two will be used in this project. This was decided early on and primarily due to the time constraints of this thesis. However, it is my opinion that this sufficiently demonstrates the potential of this workflow and system. A more detailed look at the site and the two case-study trenches will be given in chapter 4.

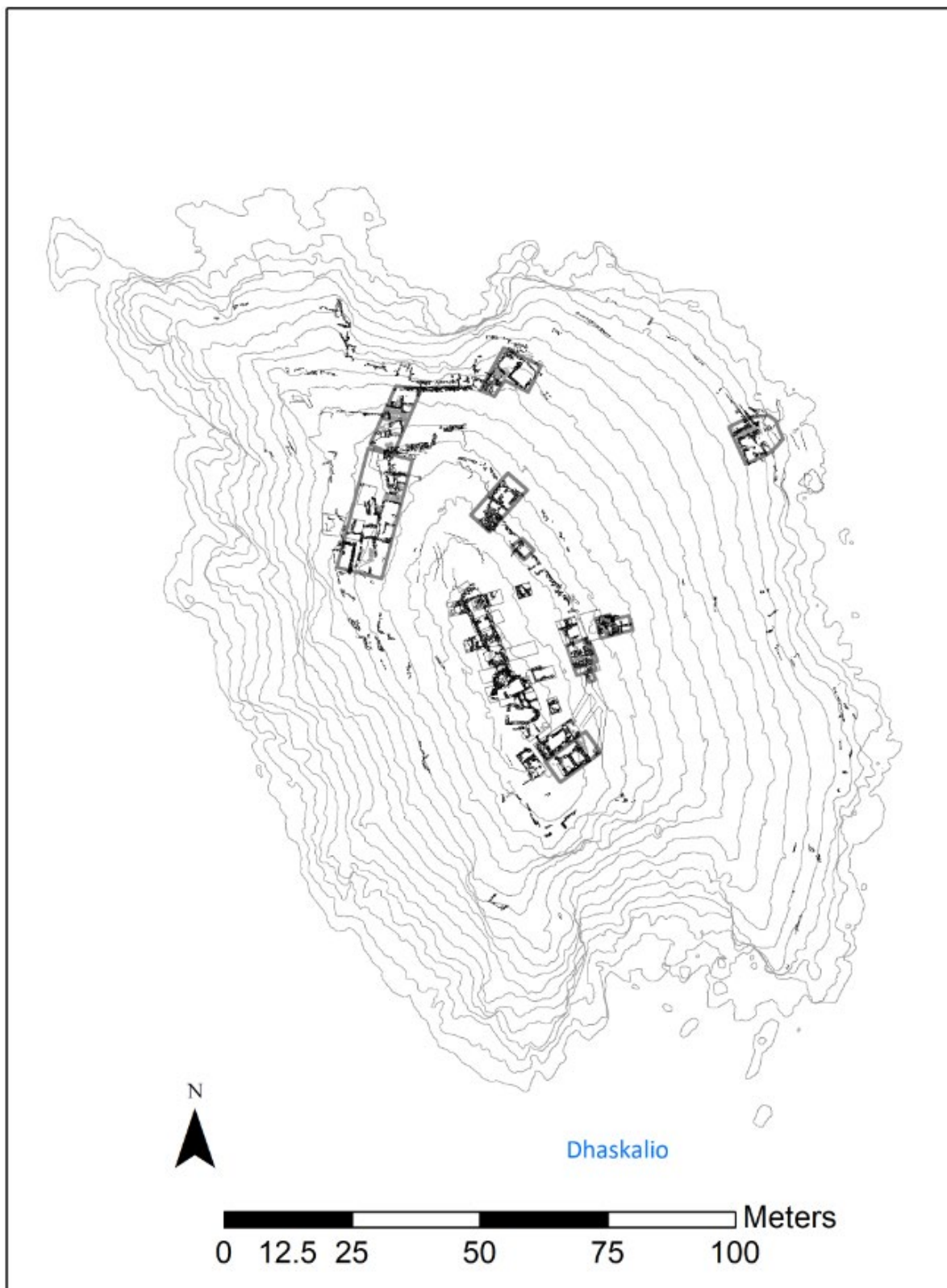


Figure 1-7 Plan of Dhaskalio showing excavation trenches; 2007-2008 and 2016-2018 seasons. Trench B (blue circle) and Trench H (yellow circle) (by author).

1.5 RESEARCH OBJECTIVES AND QUESTIONS

My thesis targets the incorporation of 3D data in archaeological research on several different levels. I aim to contribute to methodology development in spatial archaeology, explore the real-world uses of my projected model, and discuss detailed best-practice guidelines for the incorporation of this in future projects.

The overarching goal is to improve the integration of separate data classes of archaeological data - 3D data, 2D GIS, tabular finds data and measurements, photographs, and descriptions – through the creation of a unified system that streamlines interpretation and analysis into a single project centred around 3D models.

This project aims to develop a system that uses 3D models and 3D data as part of the database management itself, has an interactive interface, and most importantly, that can be used for meaningful data analysis.

By employing data from two trenches of the 2016-2018 Dhaskalio excavations as a case study, this approach is put to the test against a common objection to the use of 3D data: What does 3D contribute to research beyond flashy visualisations?

Specifically, the project investigates what contributions photogrammetry and image-based models can make to post-excavation analysis, particularly in regard to taphonomic processes and the distribution of artefacts indicating the function of space. As such, the overall questions the project aims to answer are as follows:

- What is the added value of this approach over traditional GIS methods (as discussed in section 1.3), particularly in light of post-excavation analysis?
- What are the analytical possibilities and potential of 3D documentation within the proposed system?

The analysis used within this project will include machine-learning pattern recognition in the form of density-based cluster analysis. This will be used to determine clusters of artefacts within the trenches, which in turn will be used to postulate specific purposes of space, and to determine any differences in the taphonomic processes across the site. Post-excavation analysis allows for researchers to revise data, test hypotheses, and to find meaning in the vast quantities of data collected over the course of excavation.

A further goal is to ensure the use of photogrammetric 3D models can be integrated into research and archaeological analysis across sites. I propose a detailed, re-creatable workflow to produce a 3D integrated, GIS-based database, and discuss its feasibility and challenges. As such, the final research question of this project is:

- How would this workflow be interoperable with other field methodologies and pre-existing approaches, and how well does it fit into open-science frameworks?

1.6 THESIS STRUCTURE

This thesis will be divided into a number of chapters in order to substantially discuss all facets of inquiry. Firstly, the current Introduction chapter gives an overview of the history of photogrammetry and GIS, as well as the state of current research in archaeological 3D GIS and its current applications within archaeology. Background information on the site of Dhaskalio is given though this will be discussed in greater detail in a later chapter. Primarily this chapter aims to clarify the project's research aims and objectives, giving context to what this thesis entails.

The second chapter, '3D GIS and Data Accessibility', will expand on section 1.2 of the present chapter to recount the developments of 3D GIS. As well as this, it will include as a discussion on FOSS and open science frameworks for archaeological data and how these have influenced to selection of software used within this thesis. It will further discuss some of the difficulties in using open science frameworks with large 3D datasets.

Following, Chapter 3, 'The Early Bronze Age Site of Dhaskalio' will detail the site used for the case study, putting it into context within the island of Keros. This will include its excavation history, as well as give more detail on the two trenches selected for this project, trenches B and H.

The chapter 'Data Acquisition and Methodology', chapter 4, will comprise the largest section of the thesis. It will be split into several sub-chapters. After first outlining the focus and objectives of the chapter, it will detail the methodology employed, including the data acquisition methods undertaken at Dhaskalio. Details

of the dataset will be given with focus on the photogrammetric models, as well as a discussion on the selection of an SQL-based database. Next, the software used within the project will be listed. The second half of this chapter is dedicated to the workflow created to produce the end product of an interactive 3D GIS-based excavation database.

Chapter 5, the ‘Results’ chapter, contains the outcomes of the workflow. Its aim is to exemplify the various facets of data, visual exploration tools, and data analysis techniques possible within the system. The second half of the chapter will have more specific focus on case studies to highlight the investigative tools of the 3D GIS and exemplify the usefulness of the system, by doing so demonstrating its analytical capabilities. This will be based on an artefact density cluster analysis using machine-learning tools available within the software.

Chapter 6, ‘Discussion’, will give an overview of the proposed workflow with regards to the nature of the data used. It will examine the benefits and limitations of this system in light of archaeological theory and practice, as well as to open science frameworks and data sustainability. Moreover, it will put the proposed system into context with a discussion of other projects and research in 3D GIS and the applications for 3D modelling in archaeological analysis.

The thesis will conclude in Chapter 7 ‘Conclusion’, where I will critically examine the findings of my project in regard to the aims and research questions stated above. It will end with a discussion on possible future directions for the use of 3D modelling and 3D GIS in archaeology, and finish with some last remarks on the overall project and the place of 3D modelling as an analytical research tool.

2 3D GIS AND DATA ACCESSIBILITY

This topic is briefly discussed in the preceding chapter, however its significance to this project requires it to be examined in further detail. In this short chapter I will define what 3D GIS is, how it has developed, the current software available, as well as some critiques and considerations to take into account when it is being implemented. Finally, I will examine the use of 3D GIS in the frame of data accessibility and sustainability with reference to the FAIR framework.

2.1 WHAT IS 3D GIS?

GIS is a powerful tool for capturing, storing, manipulating, and analysing spatial data (Abdul-Rahman and Pilouk 2008, 2). At its most basic level, 3D GIS is similar to 2D mapping in that it plots data along the x and y axes. However, 3D GIS goes beyond this by also incorporating the z dimension. It is able to depict location and elevation. This adds complexity to the processes involved in developing mapping layers and maintaining databases. The principal functions of a GIS are data capture, structure, manipulation, analysis, and presentation (Raper & Maguire, 1992; Abdul-Rahman & Pilouk, 2008). Ideally, a 3D GIS should have all of these functions applicable to the three-dimensional data. Van Leusten and van Gessel (2016, 34) note that the most crucial element for a 3D GIS is ‘the ability to ask and answer questions regarding the content and topological relationships of three-dimensional entities’.

The uses of 3D GIS within archaeology has already been discussed in chapter 1 and need not be repeated here. Outside the context of archaeology, 3D GIS has been used to aid government agencies in city planning, allowing architects and engineers to evaluate and analyse how changes to infrastructure will appear in the environment and for managing resources both above and below ground (Zhuang et al., 2009). It can also be useful to disaster response management, giving communities a better handle on events such as natural disasters by having detailed mapping for disaster response teams by use of best route analyses, detailed terrain mapping, and alternative routes (Hashemi Beni et al., 2007; Tiwari & Jain, 2015).

2.1.1 Software Development

The developments of 3D GIS have been pushed by the growing need for 3D information based on technological advancements in data capture. An important development has been through aerial and close-range photogrammetry, laser scanning, and survey GPS. Hardware improvements have also been imperative to these advancements. Better processors, graphics cards, RAM, and disk space have become more commonplace. A need for improved 3D functionality led various GIS developers to working on 3D software as early as the late 1980s and 1990s with the incorporation of DTMs (Digital Terrain Models) and DEMs (Digital Elevation Models), creating a 2.5D product (Abdul-Rahman and Pilouk 2008:11). Figure 2.1 illustrates the definition quality difference between 2.5D and a true 3D model, using the island of Dhaskalio as an example. As 2.5D stretches a 2D orthophoto over a DEM to produce the model, detailed information is lost such as textures and

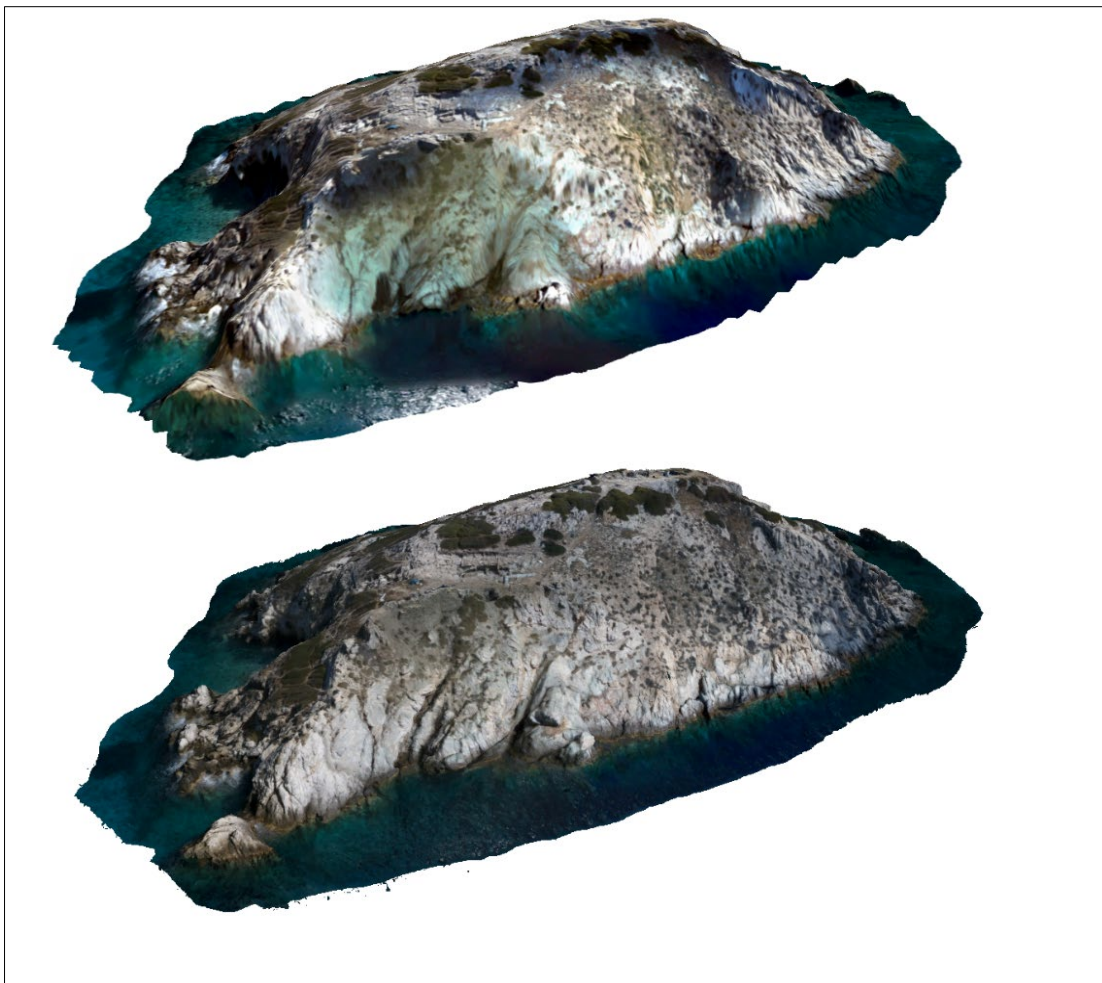


Figure 2-1 2.5D (top) and 3D (bottom) models of Dhaskalio, illustrating differences in quality (by author).

colours, as well as real three-dimensional forms. Furthermore, 2.5D does not properly represent complex relationships between data because it is based on the metric computation of coordinates rather than real topology (Abdul-Rahman & Pilouk 2008, 9). Meanwhile, the true 3D model is able to capture these details for a photorealistic and measurable representation of the island.

By the mid-to-late 2000s several commercially available GIS software provided various levels of support for 3D data, typically limited to 2.5D or crude versions of 3D. For example, ArcView with the ArcScene and 3D analyst extensions, VirtualGIS, and MapInfo. More recent updates to these have seen improvements of overall 3D capabilities with software such as ArcScene being able to handle and examine textured photogrammetric models and LIDAR data. Further advancements have included the use of HTML5 as a canvas for creating online GIS with support for 3D, providing custom solutions to GIS-based issues (Boulos et al., 2010; Mete et al., 2018).

While by no means exhaustive, this section has summed up the question of ‘what is 3D GIS’ by focusing the capabilities it should have in data analysis and the representation of 3D data. A short history of the software developments has also been presented to provide context in where 3D GIS currently stands and what software other projects have appropriated. In the following section 3D GIS software will be discussed through the lens of data accessibility and sustainability.

2.2 FOSS, DATA ACCESSIBILITY AND SUSTAINABILITY

2.2.1 Software Selection: Open-Source vs Proprietary Software

FOSS (Free and open-source software) refers to any software that is freely licensed to use, copy, study, and modify the software and that the software’s source code is openly shared. In contrast, proprietary software is set under restrictive copyright licensing where the source code is typically hidden. In terms of GIS there are several FOSS software available. Suites such as GRASS and QGIS are common among archaeologists, though have limited functionality when it comes to 3D data. While GRASS supports common 3D file types such as Collada and wavefront OBJ using the wxGUI 3D View Mode extension, this is still under development and not

all functionalities have been implemented yet, including the automatic application of texture files (<https://grass.osgeo.org>, accessed 9 August 2020). The common open-source GIS, QGIS, is currently limited to 2.5D support rather than fully integrated 3D, though does include a separate 3D window that runs alongside the 2D viewer. Recently, QGIS has announced they are working on an update to incorporate point cloud data, though it is unclear when this will be released (<https://github.com/qgis>, accessed 12 August 2020).

At present, proprietary software has a wider scope and analysis types and better integration for more complex 3D geometries in a GIS environment. Esri's ArcGIS, a proprietary software commonly used by archaeologists, allows one to overlay layers of data in a 3D environment including textured 3D models, in the extension ArcScene. However, ArcScene runs in a separate application to ArcMap and lacks some basic and important functions such as labelling and symbology tools, making it unsuitable as a database and means one must swap between the two extensions for a comprehensive view of all data. Further ArcScene's support for 3D file types is limited to few, including 3DS (3D Studio Max), WRL (VRML), SKP (SketchUp), FLT (OpenFlight), and DAE (Collada). CityEngine, a software with a procedural modelling approach to create detailed large-scale 3D models with georeferencing (<https://doc.arcgis.com>, accessed 14 July 2020), for example, has had success in archaeological research and the reconstruction of ancient urban environments (Piccoli, 2018). The software has recently been integrated into Esri's latest GIS software, ArcGIS Pro, where its tools are available in a robust GIS environment along with more comprehensive 3D tools for visualisation, mapping, and analysis (<https://www.esri.com/about/newsroom>, accessed 14 July 2020). It is this software, ArcGIS Pro, that this project utilises. While open-source GIS options were reviewed, ArcGIS Pro proved to have the most robust 3D capabilities, support the most data types with the added support for .obj files, and importantly, have a robust set of documentation. Furthermore, ArcGIS Pro retains the definition of a model's texture, which I see as an important aspect for the analysis of stratigraphic layers. It is this author's hope, however, that once a robust, stable, and fully integrated 3D is available in FOSS programs, the workflow presented in this thesis will be re-creatable in the FOSS platform with minimal alterations.

2.2.2 Storing and Sharing Data into the Future

The integration of 3D modelling into the archaeological suite of tools has created new issues to address regarding the storage and sustainability of three-dimensional files. 3D technologies have revolutionised the way that we as archaeologists collect data. These high volumes of complex data have brought with them the critical challenge of management and accessibility for their own sustainability (Richards-Rissetto & von Schwerin, 2017).

The MayaArch3D Project addressed issues in data management of large quantities of 3D data and put forth that the current limitations to 3D accessibility are embedded in the institutional habits of “best-practice” data management and standardised file formats. They suggest that more open frameworks to promote data reuse within archived data would promote accessibility and future engagement (Richards-Rissetto & von Schwerin, 2017). Most recently, Pilzecker (2020, 106-108) addressed these same issues with a more structured and definitive methodology. He concluded that a 3D dataset should adhere to four steps for digital preservation. In summary these are that firstly, one must address ethical and legal considerations, including the sensitivity of the dataset. Secondly, the restructuring of directories and file names to ensure human and computer readability. Thirdly, file formats used in exporting 3D files should be preservation friendly with the suggestion of either FBX or OBJ types. OBJ file types are also the preferred 3D file for archiving by the Archaeological Data Service (ADS) (ADS 2019). The final recommendation is to make available three levels of metadata so there is adequate information for outside researchers to understand and replicate the 3D dataset. Pilzecker stresses that archaeologists must facilitate the long-term readability of 3D files as much as possible to ensure they are a sustainable method of research for future generations. However, the matter of a place to store such large and complex data is another issue. Attention to openness and accessibility has been promoted by the FAIR Data Principles, suggested by Wilkinson et al. (2016), to make archaeological data findable, accessible, interoperable, and reusable. The establishment of digital archives such as the ADS for UK data, the ARIADNE (Advanced Research Infrastructure for Archaeological Data Networking in Europe) framework, and the EASY archive run by the Data Archiving and Networked Services (DANS) all contain the infrastructure to support three-dimensional data

with the shared aim to better disseminate archaeological datasets in the wider research community while preserving data. However, many of these archives have limits imposed for file sizes such as ADS, while the EASY framework allows an individual researcher to deposit up to 100 GB of data free (<https://dans.knaw.nl>, accessed 13 December 2020). A large project, such as that of this thesis, with a high quantity of 3D models could expect to eventually reach this limit.

While this project makes no aim for setting new guidelines or advice on the use of FOSS frameworks or new visions of a sustainability model, it is hoped that once stable frameworks and archiving methods capable of handling larger datasets become available this project type can be more easily shared. Unfortunately, the limited choices available for 3D GIS software has meant this project does not fulfil all requirements of a FOSS system, though substantial effort has been made to select file types that have a long history of use and appear to have continued support in the future, such as using OBJ file types for the 3D models and an SQL database. With this in mind, a more general workflow for future GIS projects will be proposed alongside the software specific one to this project in chapter 4. Furthermore, while I acknowledge the importance of the FAIR principles and making archaeological datasets accessible to outside researchers, it is not possible to adhere to these by submitting the 2016-2018 Dhaskalio project files to one of the above-mentioned digital archives in its present state. The data from this excavation has not yet been published by the excavation team, and importantly the data contains sensitive information for a site that has a history of illegal excavations and looting, as will be discussed in the following chapter. Nevertheless, it is feasible that once the project has been completed and published that the 3D GIS data could be made available within this framework.

3 THE EARLY BRONZE AGE SITE OF DHASKALIO, GREECE

In this chapter I will give an overview of the Early Bronze Age (c. 3300-2200 BCE) archaeological site Dhaskalio, where the data being used in this project originates. While a brief overview of the site was made in the introductory chapter, here I will give a summary of some of the excavation history and more specifically outline the two trenches used as case studies, trenches B and H.

3.1 KEROS: KAVOS AND DHASKALIO

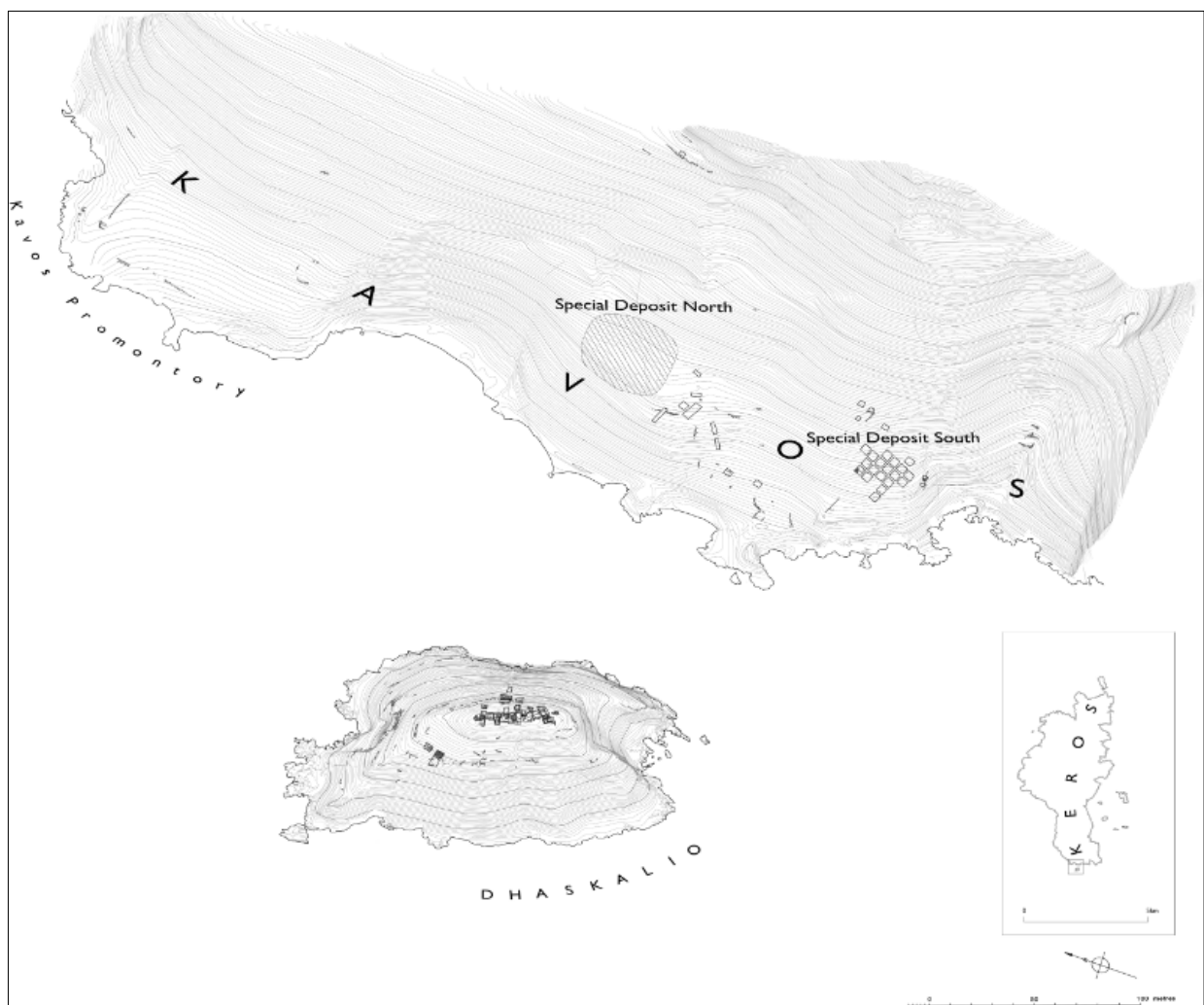


Figure 3-1 Dhaskalio and Kavos from the west. Contours at 0.5 m and 5. intervals. (From Renfrew et al. 2009, fig. 1, 29.)

To understand the site in question, Dhaskalio, one must first appreciate its position within the broader context of the island of Keros. While in the present-day Keros and Dhaskalio appear as two different sites, in prehistoric times, the two areas were joined by a natural promontory, which due to shifting sea changes has now disappeared. (Dixon & Kinnaird, 2013). Keros is a small, and today uninhabited, island in the southern Cyclades in the Aegean. In 1963 indications of looting from the site came into official notice (Doumas, 2007) and rescue excavations by archaeologists began. The site consists of two ‘special deposits’, and a small cemetery located on the beach Kavos, and a large, terraced, settlement on the islet Dhaskalio. The western coast of the island, Kavos, has been recognised as the first inter-regional ritual centre for the EBA Aegean, and has been interpreted as the earliest maritime sanctuary. This is based on the deposits of broken marble vessels and figurines believed to have been brought to the site from across the Aegean to be deposited at Kavos (Renfrew et al., 2012). It has been made famous by the ‘Keros hoard’, a large amount of Cycladic marble folded-arm figurines, most of which were looted from the site (Renfrew et al., 2016; Sotirakopoulou & Sotirakopoulou, 2006). Dhaskalio lies 90 m west of Keros, adjacent to the special deposits of Kavos. The site will be outlined in more detail in the section below.



Figure 3-2 View of Dhaskalio from the Special Deposit South on Kavos (from Renfrew et al. 2012, fig. 5, 151.)

3.2 PREVIOUS RESEARCH

The first excavations of Dhaskalio, lasting only a few days, took place in 1963 by Doulas where a single building on the peak of the hill was explored (Doulas, 2007). Two decades later, in 1987 a brief unsystematic survey of the island confirmed that the site possessed a huge amount of EBA material, though its relationship to Kavos was not yet definitive (Whitelaw, 2007). New excavations began from 2007-2008 by the Cambridge Keros Project which set out to investigate the settlement site in more detail (Renfrew et al., 2009). The results of this investigation suggested the potential of the site to advance our current understanding of Early Cycladic (EC) archaeology. Extensive and well-preserved remains from the EBA are present, with very little material from later periods. There is a small Byzantine chapel on the peak of the island, but no other structures relating to later periods of occupation have been uncovered. Investigations soon established that Dhaskalio was a major EC settlement with immense stone architecture and well-planned terrace walls, the marble of which was imported mostly from the nearby islands of Paros and Naxos (Boyd, 2013). Calibrated radiocarbon dating combined with ceramic typological analysis determined Dhaskalio's chronology, stretching to the middle EC period, c. 2700-2300 BCE (fig. 3.3). Archaeologists returned to excavate the site between 2016-2018 with the aim of establishing the range of activities on the site and the ways in which people moved around it. These latest excavations revealed remarkable evidence for architecture and town planning, craft activities such as metallurgy, and the widespread import of raw materials as well as finished goods. It appears to be the first clear evidence for incipient urbanisation in the EC (<https://chronique.efa.gr>, accessed 2 December 2020).

Transition	Weighted mean	Median	95% probability range	Approximate consensus
Beginning of Dhaskalio Phase A	2746 BC	2742 BC	2885–2622 BC	c. 2750 BC
Dhaskalio Phase A/B transition	2540 BC	2536 BC	2609–2482 BC	c. 2550 BC
Dhaskalio Phase B/C transition	2391 BC	2392 BC	2451–2322 BC	c. 2400 BC
End of Dhaskalio Phase C	2290 BC	2292 BC	2387–2193 BC	c. 2300 BC

Figure 3-3 Chronology the phases at Dhaskalio. (From Renfrew et al., 2012, table 6, 155.)

3.3 OVERVIEW OF TRENCHES

The 2016-2018 excavations for which this thesis focuses on contained eight trenches - A, B, C, E, F, H, L, and N, as well as two smaller test sondage trenches, SA and SB. As discussed in the introductory chapter, the decision was made to select two trenches to use as case studies to showcase the proposed workflow. In large this was done due to the time constraints of this thesis and the Keros Project has the intention to add the remainder of the trenches into the GIS in the future.

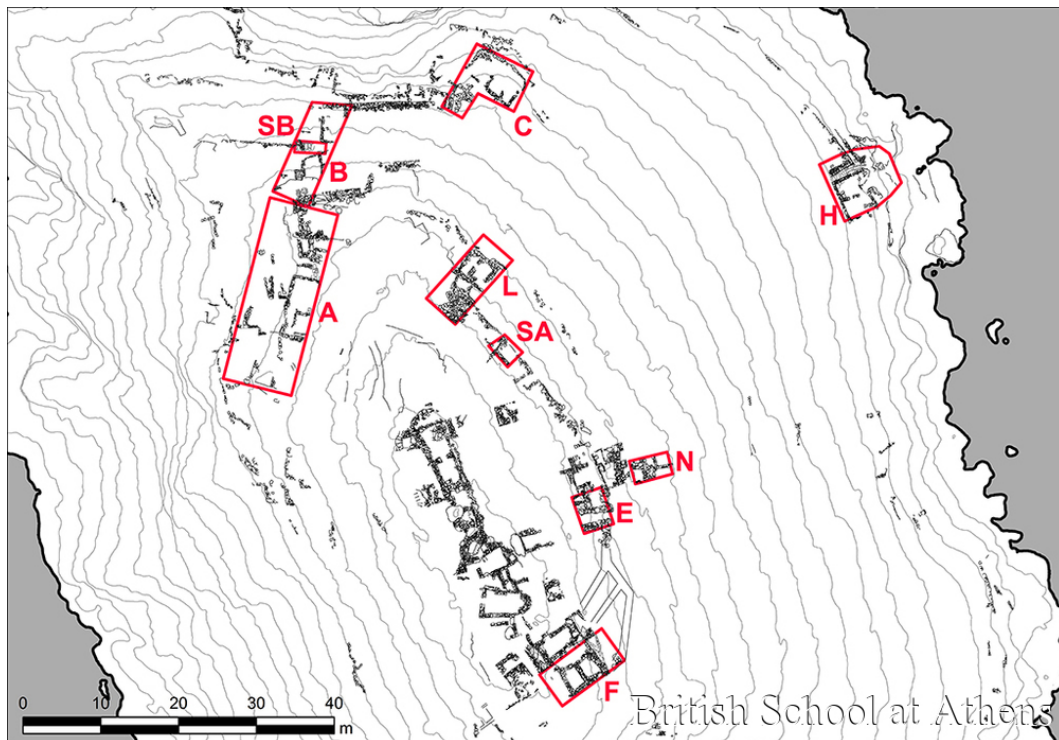


Figure 3-4 Trenches opened in 2016-2018 seasons labelled in red (from <https://chronique.efa.gr/?kroute=report&id=6541#true-1>)

3.3.1 Trench B

Trench B is located on the northern side of Dhaskalio on a very steep slope. It measured 14x5m, overall encompassing 70m². The site was initially chosen due to the large marble terracing walls 4 and 102, which run around the northern and western sides of the island. It was hoped that Trench B would help to understand the patterns of movement around the island.



Figure 3-5 Collapsed staircase in Trench B, showing different elevation levels of rooms and areas (by author)

Four rooms and several external areas were revealed, constructed at different elevations connected by a marble staircase (fig. 3.4). The flight of steps at the bottom of the trench lead up to an area of flagstones marked by four petroglyphs at the point where the path divides, connecting to a passageway that offers alternate routes of movement. The staircase covered a drain, the end point of which can be seen a few metres south of the trench on the northern face of the island. Room 3, the southern upper end of the trench, had several interesting features built into the bedrock including a clay hearth and a bench or work surface where worked stones, a large grinder, and storage vessels were uncovered.

Excavation has shown that Dhaskalio was submitted to extreme taphonomic processes post-abandonment, with trench B suffering due to the steepness of the lower edge of the islet for which it is located. The trench was subjected to strong winds from the north and it is clear that the unstable geomorphology of the island affected the site, where remnants of terracing walls and massive collapsed limestone boulders lie down the cliff face (see fig. 3.7).

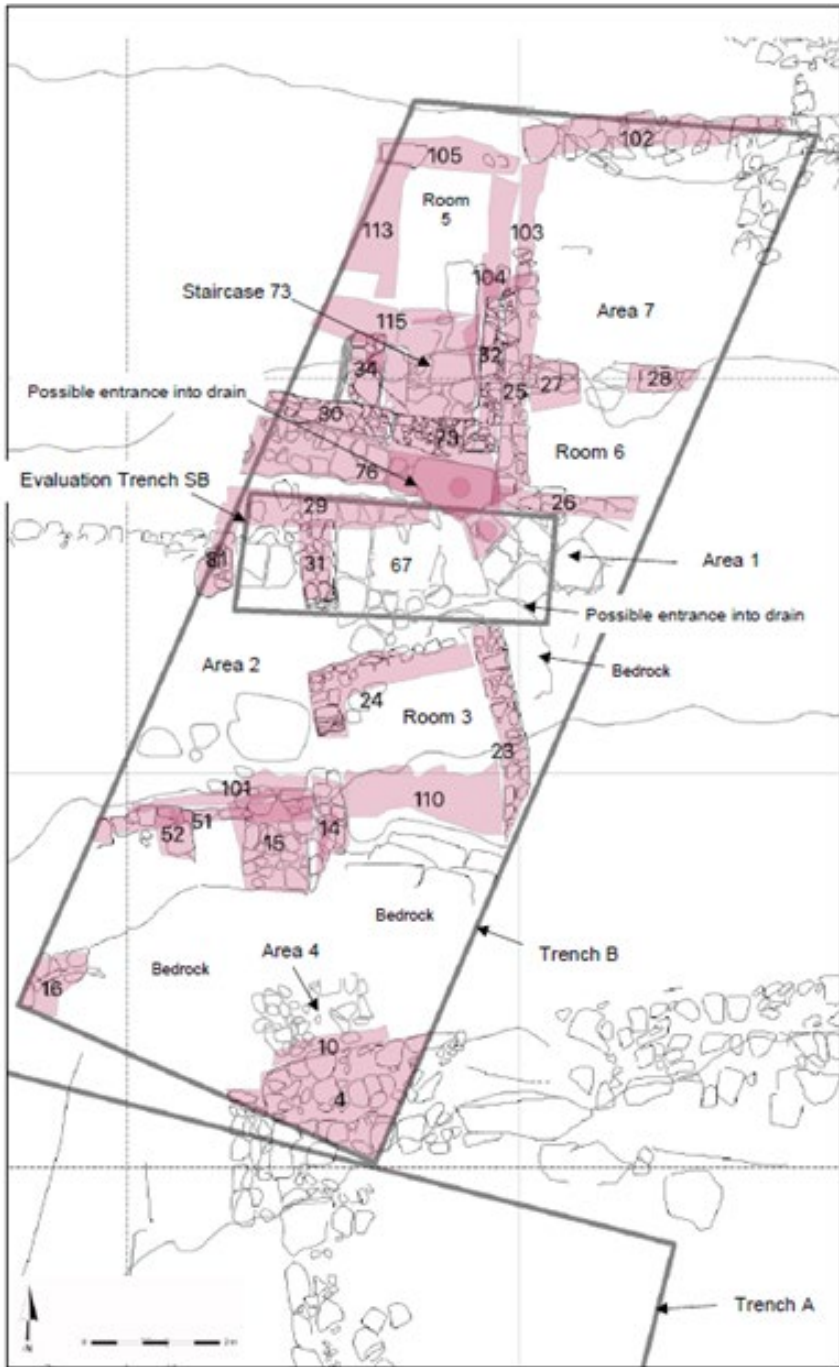


Figure 3-6 Map of Trench B with features and areas labelled. Walls coloured pink. (by author)



Figure 3-7 Photo of Dhaskalio taken from UAV showing trench B (circled) in its position above the steep cliff face (by author)

3.3.2 Trench H

Trench H is situated on the north-east limit of Dhaskalio, facing Kavos. Excavation of the trench revealed well-preserved complex architecture and led to the identification of five areas (fig. 3.9). These include two rooms which



Figure 3-8 Trench H, view from the North (by author)

have known three phases of occupation (Area 1), a staircase with an impressive drainage system beneath and which may constitute the entrance to the island from

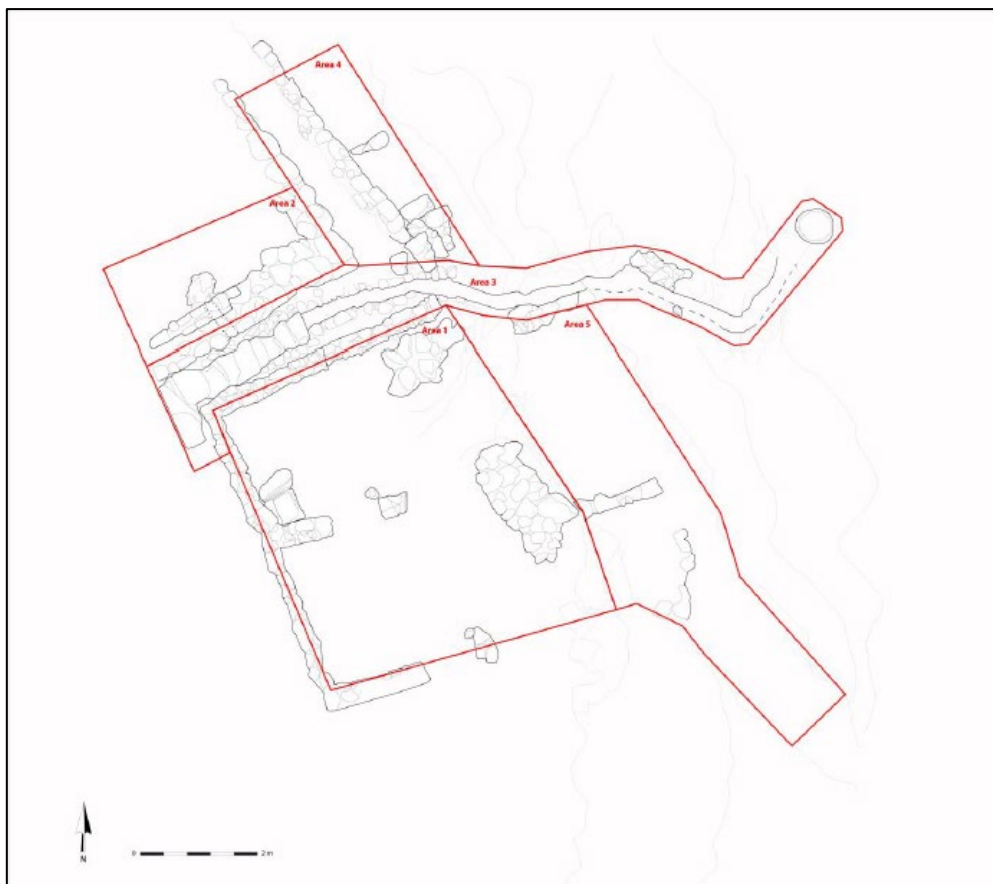


Figure 3-9 Plan of Trench H showing different designated areas (by author)

Kavos (Area 3), a space in the north presumed to be a room (Area 2), an extension of the trench to the north-east showing the terracing system (area 4), and a south-eastern extension that links the entrance of Dhaskalio to the isthmus (Area 5). The ceramic analysis indicates that most stratigraphic units relate to Phase A and Phase B. Moreover, the excavations of several relayed floor levels in the two rooms to the south of the entrance (Area 1) revealed two metallurgical hearths cut into the bedrock, perhaps indicating a metallurgical workshop, the study of which could provide better understanding of EBA metal-processing technologies.

The well-built staircase with an underlying drainage system seems to suggest a predetermined understanding of routes of movement at Dhaskalio as well as a comprehension of engineering and water management. Meanwhile, a large number of imported ceramic vessels found in Room 1, including three imported in-situ pithoi, indicate pan-Aegean connections.

Taphonomic processes have degraded the stratigraphy in the eastern half of the trench, as is made clear in fig. 3.8 and fig. 3.10, where the architecture and strata have clearly been weathered away. Despite this, the western half of the trench is remarkably intact, where well-preserving laminated stratigraphy was documented. The excavation to bedrock levels will further enable a more complete understanding of the site processes over time, from its initial occupation to abandonment.

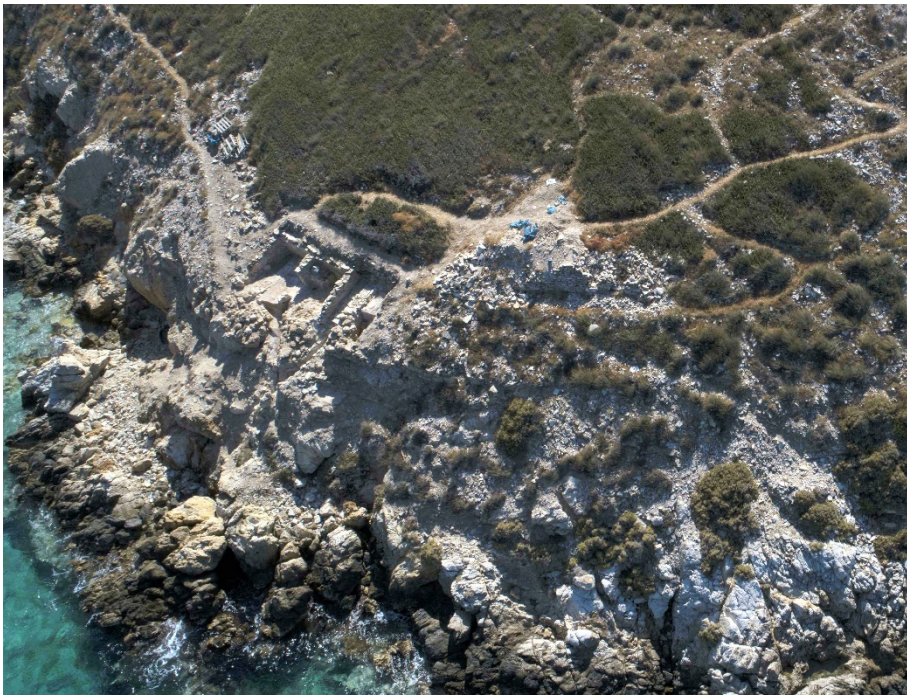


Figure 3-10 Trench H from above, exemplifying the degradation of the eastern side and proximity to the water. (by author)

4 DATA ACQUISITION AND METHODOLOGY

4.1 INTRODUCTION, FOCUS AND OBJECTIVES

In this chapter I will review the methods of documentation and data processing undertaken to create this integrated 3D GIS database. This includes the relevant on-site documentation used on Dhaskalio in the 2016-2018 field seasons and the steps taken in the photogrammetry processing. More than the 3D modelling, this chapter will discuss the SQLite/Spatialite database used by the project and the different types of data used to create the interactive, living database of Dhaskalio. The aim of this research is to create a workflow that is feasible and effective for archaeological data, with the potential to be integrated by future archaeological projects. This project is also relevant to streamlining a process that can otherwise be overwhelmingly time consuming³. The intention here is to have the relevant site data together in one system that operates efficiently. Moreover, this should be a system that is easy to set up making it user-friendly for users who are not IT specialists. Ideally, this would be done over the entire site. As previously discussed, due to the high amount of data and time constraints for completing this thesis, this project is a prototype based on two trenches that can be considered representative of the site. If done site-wide, this method would surely aid with interpreting site formation processes, as well as placing trench data in a wider intra-site context and could be used as a central part of the whole site interpretative process, as is the intention of the Keros Project in the future.

4.2 DHASKALIO DOCUMENTATION METHODS AND DATA ACQUISITION

This subsection will outline the different methods of data acquisition for data transparency purposes, including the various software used. The methodological steps taken in creating the three-dimensional database will follow.

³ Rather than beginning a query in a separate database, such as Access, finding and filtering to these items in ArcScene or GIS, and then perhaps opening a 3D file in an outside software such as CloudCompare, opening the corresponding field photographs, then reviewing the information by going between these programs -

4.2.1 The Dhaskalio Dataset

The dataset used in this project is extensive. The types of data and numbers of files are summarised in Table 4.1, below. The collection of the 3D data was done in the field between 2016-2018. The Keros Project had intended from the outset to build an extensive three-dimensional spatial record of the project area which would include the natural topography, architectural features, and all stratigraphic contexts. This was a facet of the holistic approach taken to recording and information flow, which necessitated an almost entirely digital recording strategy by which data could be shared easily between excavators and specialists (Boyd et al., Forthcoming). This was done largely by using the iPad application, iDig⁴. The app automatically assigned unique identifier codes to each entry and allowed users to relate entries to one another, which in turn meant it could automatically produce stratigraphic and temporal matrices (Hartzler & Verigakis, 2016). Topographic data could be recorded directly into the system by connecting the iPad to a Total Station via

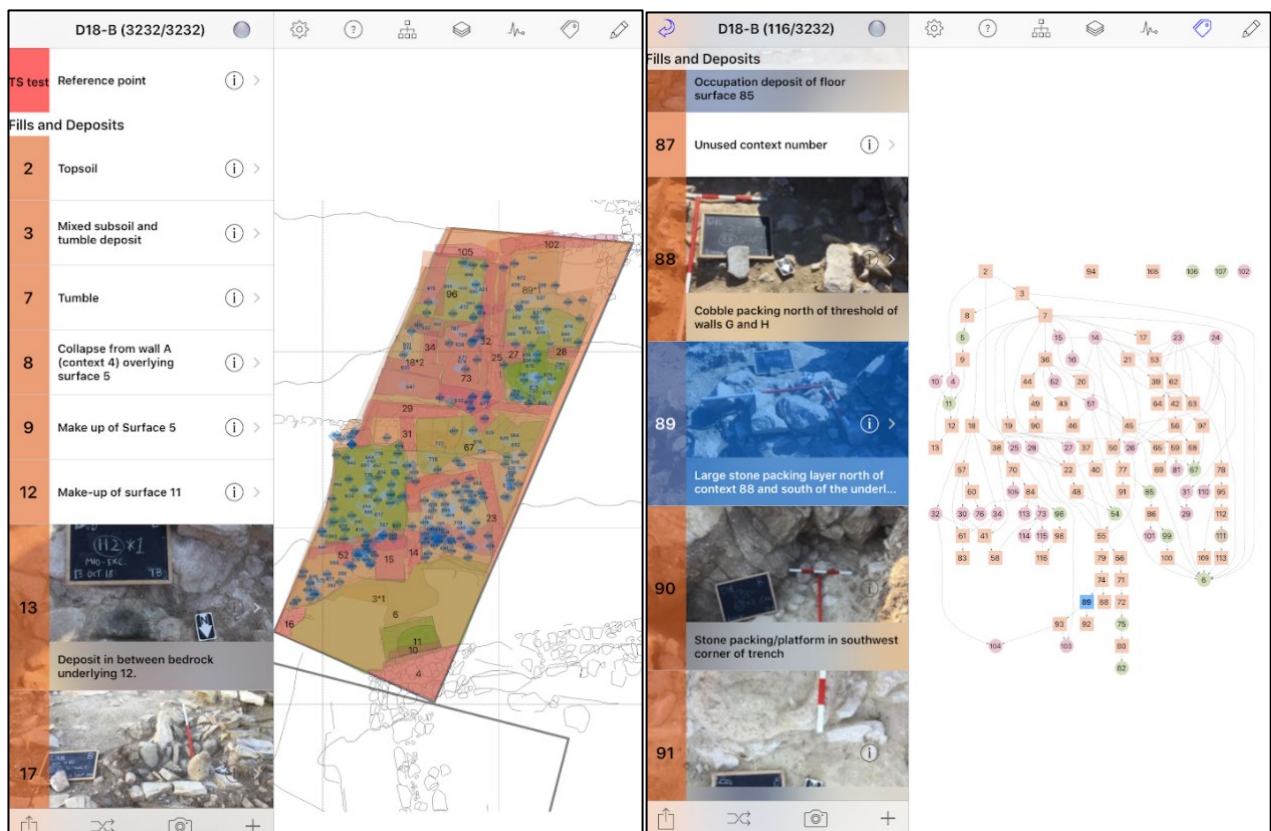


Figure 4-1 Screenshot of iDig showing plan of Trench B with all layers turned on (left) and spatial matrix created by iDig (right)

⁴ iDig was developed by Bruce Hartzler for the American School at Athens' excavations at the Athenian Agora and is available for free on the App Store.

Bluetooth or USB, where the XYZ points were added to create polygons for the boundaries of contexts and structures, or to create point data to record artefacts and take context levels. Each individual iPad could be synchronised with the others as much as needed, which not only meant that all site data was available to everyone holding an iPad, but that several backups were available at any one time, should anything go awry. The data from the iDig system was exported into a Postgres SQL database, which will be discussed in section 4.2.3.

4.2.2 The Photogrammetry

An intensive photogrammetry recording strategy complemented the other digital recording methodologies. The Keros Project established a documentation workflow centred around the consistent and rigorous use of structure-from-motion photogrammetry where the documentation workflow was kept consistent throughout excavation campaigns (Boyd et al., Forthcoming). At the beginning of each excavation season, coded targets were fixed at approximately 2 m to 3.5 m intervals surrounding and within the trench (generally stuck on fixed architecture), and each was georeferenced using the Total Station and stored in a dedicated 'Photogrammetry' trench in iDig. Well measured coded targets greatly increase the accuracy of photogrammetric reconstructions and speed up the processing time, which was central to the project's objectives (Sapirstein & Murray, 2017). Three targets were used as the minimum number required to produce a georeferenced scene (Sapirstein & Murray, 2017), and

typically 25-100 individual photos were used to create each model depending on the size and detail necessary in the scene. Contexts were captured in each trench by a trained field member using a handheld digital camera and every afternoon the images were transferred to the lab's main processing computer. The context folders were shared via a local network and a small team of photogrammetry specialists, managed by myself from 2017, processed each context into a 3D model using

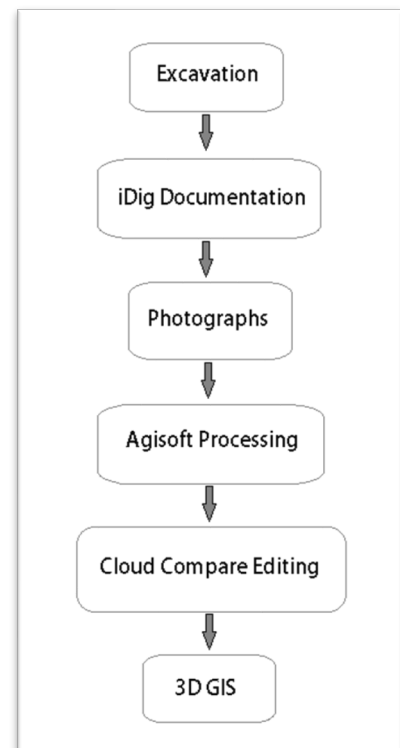


Figure 4-2 Flowchart of Dhaskalio's photogrammetric processing

Agisoft Photoscan (now Metashape) aided by the use of a Python scripted batch process to maintain a standard procedure and output. This resulted in a textured 3D mesh of each context's opening surface which also represented the bottom of the layer above (saved as an .obj file), a DEM (1 cm resolution), and an orthophoto (2 mm/pixel resolution) which were then exported for archiving. Each 3D model was then imported into CloudCompare where it was edited as needed. This included realigning the mesh when necessary⁵ and cropping the mesh to the context's boundaries. Finally, the file could be saved and was ready to be used within the GIS, which will be discussed below in section 4.4.

Concerns relating to data quality should certainly be addressed. There is undoubtedly irregularity of colours between the textured 3D models of contexts due to uncontrollable variables, particularly the time of day that the image sets were taken. While some projects (see Galeazzi 2016; Sapirstein & Murray 2017; Waagen 2019) have attempted to minimise these disparities, they often involved daily drone captures of the site at a set time and do not capture each excavated layer in the stratigraphy. This project was far more ambitious, creating models of each excavated stratum, meaning that waiting for the ideal lighting was not an option, and nor would it be for most projects. This meant that the photo sequences were taken as soon as the new context was exposed, regardless of the lighting. Further,

to minimise the error projection of the georeferencing in the production stage, an absolute maximum error of 0.04 m was

Markers	Error (m)	Error (pix)	X (m)	Y (m)
✓ target 45	0.005794	0.645	221.059000	3505.131000
✓ target 48	0.006171	0.534	221.837000	3504.978000
✓ target 50	0.015911	0.613	224.866000	3504.395000
✓ target 52	0.008258	0.966	222.264000	3506.712000
✓ target 54	0.007528	0.202	230.990000	3506.782000
Total Error				
Control points	0.010256	0.706		
Check points				

accepted in Agisoft, *Figure 4-3 Error Margin example per metre and pixel as seen in Agisoft Metashape for Trench H 2018 end of excavation model*

⁵ Most models needed to be aligned a minimal amount, and the final model of the fully excavated trench was used as the basis for the alignment. In CloudCompare this can be done easily and automatically using the 'align clouds' tool, which uses similar/identical points from both clouds to readjust one. The parameters are chosen by the user. In this case solid wall architecture was used as it was unlikely to have shifted during excavation.

though this error was typically far less, as seen in an example from fig. 4.3.

4.2.3 SQL Databases: SQLite vs Postgres

The site data from Dhaskalio was made into an SQL-based database. There are many options for databases using this language, some simple and others far more complex. The main benefit for connecting to an external SQL relational database in this project (beyond good database management practices), is that it means that the data can be manipulated in the ‘back-end’ by anyone with login access to the database, and then can be opened in the preferred tool for visualisation, manipulation, and analysis in the ‘front end’ software. In this project, two database types were tested to ascertain which would work best in the workflow. The first tested was the database management system SQLite, using its spatial geometry extension SpatiaLite. This was chosen as it offers simplicity in its function as a single, sharable file rather than a complex client-based database schema. An additional benefit of an SQLite database is that it can be viewed and edited without the need for special or complex software, nor an internet connection. Once created, the database can be viewed, queried, and edited using an exterior software – in this case, DB Browser. Furthermore, the SQLite database can easily be imported into Microsoft Access, GIS, and other programs that allow SQL-based data manipulation and database connections. Moreover, should a client-based relational database ever be required, it is simple to export the SQLite file into a plain SQL dump file which can then be imported to a server-based database.

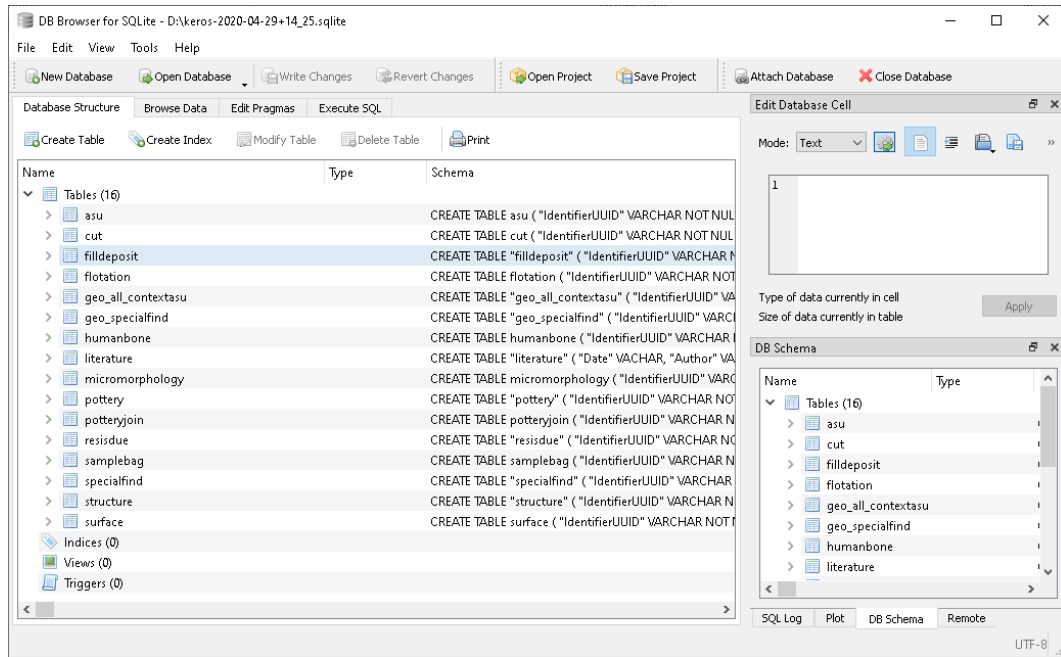


Figure 4-4 A screenshot of DB Browser showing the 2016-2018 Dhaskalio database as an SQLite file schema

The second database option tested was running a server-based SQL database using PostgreSQL with a PostGIS extension. This is an open-source object-relational database system, with the extension adding support for storing geographic objects within the database. The database itself is hosted on a server⁶ and accessed via PostgreSQL's web-browser administrative tool, 'pgAdmin' (fig. 4.5). Similarly to SQLite, PostgreSQL allows a user to create the database by importing an SQL 'dump file' so one can easily transfer an existing SQL database to this format if desired. This would then allow for easy accessibility by using the login credentials of the file to access the data. A direct comparison between the two database types is provided in table 4.1, below.

⁶ For this project Google Clouds server was used, which provides a 90-day free trial and then a low-cost solution for server hosting based on the GBs of data stored, should the free threshold be reached.

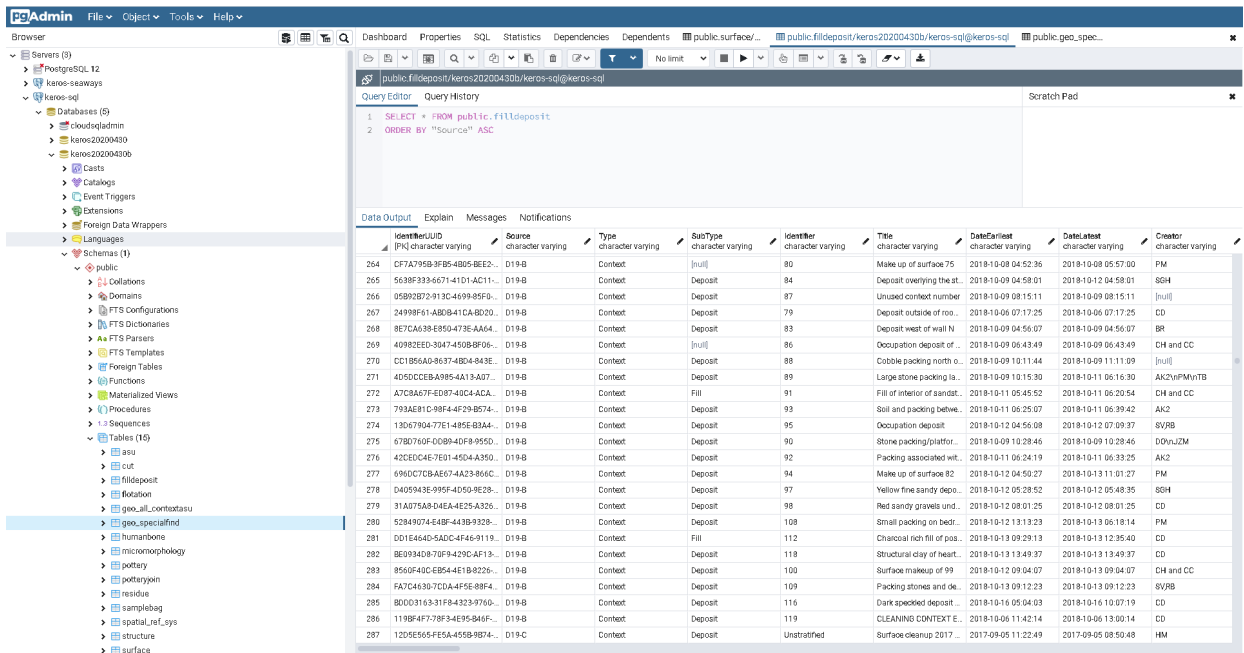


Figure 4-5 PostgreSQL database viewed in PG Admin.

A key aspect of this project has been to make a ‘living’ database. This means that the database should be able to grow and be modified over time, allowing access to do so to multiple users, possibly at the same time. Due to this, the latter PostgreSQL server-based database was selected as it was the most useful to fulfil this project’s objectives.

	SQLite	PostgreSQL
Single File Set Up	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Offline Access	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Continuously Updates Changes	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Accessible by Many Users and Software at Once	<input type="checkbox"/>	<input checked="" type="checkbox"/>
FOSS	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Table 4-1 Table summarising the differences between SQLite and PostgreSQL database types

4.2.4 Photographs, Literature, and Other Files

A large number of other general files make up a significant part of the project’s data from the 2016-2018 seasons. These were provided by the Keros Project and include more than 1000 field photographs and over 1000 photographs of the SF artefacts from trenches B and H, various documents related to the trenches such as end of season reports, trench notebooks, and finalised Harris Matrices. Digital polyline plan drawings of the site’s architecture drawn by the site architect using CAD, as well as various PDFs of literature published about the site. These are summarised in Table 4.1, below. Note that where things are stored on an

external HDD, this workflow adds them into the internal geodatabase of the 3D GIS.

Table 4-2 Table summarising data types used in this project

DATA	FILE	TYPE	ACQUISITION METHOD	NUMBER OF FILES	STORAGE LOCATION
PHOTOGRAMMETRY	OBJ	Multipatch	Photographs/Agisoft Metashape	291	External HDD > 3D GIS
ORTHOPHOTOS	TIFF		Photogrammetry models		External HDD > 3D GIS
DEMS	TIFF		Photogrammetry models		External HDD > 3D GIS
EXCAVATION DATABASE	SQL		Exported from iDig	1 file containing 15 tables	PostgreSQL database
SPECIAL FIND DATA	ShapeFile	PointXYZ	Total Station/exported from iDig	1214 points	PostgreSQL database
FIELD PHOTOGRAPHS	JPG		Field recording	>1000	External HDD > 3D GIS
SPECIAL FIND PHOTOGRAPHS	JPG		Finds recording	1188	External HDD > 3D GIS
TRENCH REPORTS	PDF		Field recording	16	External HDD > 3D GIS
PLAN DRAWINGS	Shapefile	Polyline	Orthophotos/drawn		External HDD > 3D GIS
LITERATURE	PDF		NA		External HDD > 3D GIS

4.3 SOFTWARE

Some of the underlying software used in this project has already been mentioned above. I will now discuss them in more detail. The main software used is ArcGIS Pro, which is an updated version of Esri's well-known GIS software and was first released in 2015 with the intention of eventually replacing ArcMap. The program incorporates the functions of ArcMap and ArcScene in one, allowing for both 2D and 3D data processing in a single environment. ArcGIS Pro can be made available with a typical student licence which is commonly available to universities and their students. Issues relating to the availability of proprietary software have been discussed earlier in chapter 2, where the choice of this software was justified. In sum, it is certainly the most robust and straightforward 3D GIS currently on the market.

For testing the SQLite database, DB Browser for SQLite was used. It is an open-source software created by several contributing developers and has been available since 2013 via GitHub. It offers a simple browsing and editing tool for SQLite databases, including the option to create and edit tables and add spatial data via the SpatialLite extension.

As mentioned above, PostgreSQL is an open source object-relational database system that uses an extended SQL language. It was initially developed by a team at the University of California at Berkley in the 1980s and has since become a popular database storage tool. It also has powerful add-ons such as PostGIS, a geospatial database extender which allows for geographic location queries to be run.

Both Agisoft Metashape and CloudCompare are important to this project, however the workflow presented below assumes that the user has already created and edited their photogrammetric data as needed. As such, they will not be a part of the workflow outline, though I see it necessary to mention them.

SOFTWARE NAME	MANUFACTURER	VERSION	TYPE	FOSS	WEBSITE
ARCGIS PRO	Esri	2.6.2	GIS	No	https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources
AGISOFT METASHAPE	Agisoft	1.6.2	Photogrammetry	No	https://www.agisoft.com/
DB BROWSER FOR SQLITE	DB Browser for SQLITE	3.12.0	Relational Database Viewer	Yes	https://sqlitebrowser.org/
CLOUDCOMPARE	CloudCompare	2.11	Point Cloud Viewer	Yes	https://www.danielgm.net/cc/
POSTGRESQL PG ADMIN	PostgreSQL Global Development Group	13.0	Relational Database System	Yes	https://www.postgresql.org/

Table 4-3 Software used by in this project

4.4 WORKFLOW

This section is dedicated to the workflow used to create this fully integrated 3D GIS database system, which is software dependant on ArcGIS Pro. It is my intention that this workflow can be used by other projects with similar

datasets, which will be discussed further towards the end of this section. It is hoped that the basic steps could be repeated in open access versions of GIS when a more robust integration of 3D data is made available. Prior to beginning this thesis, I had been supplied the SQL database schema for the project. As well as this, I already had access to the 3D models and had edited them. Each model had been aligned and cropped to the context boundaries, then exported as an .obj file. Much of the workflow has been optimised by using Python scripts available through ESRI's website⁷, however some facets of data require more time-consuming manual uploads and configuration. Figure 4.6 summarises the workflow with the ArcGIS Pro specific steps and more general steps that could be applied to other software in red.

⁷ The scripts shown below use this project's data as examples, but the standard syntax for each tool is found easily online via ESRI's website.

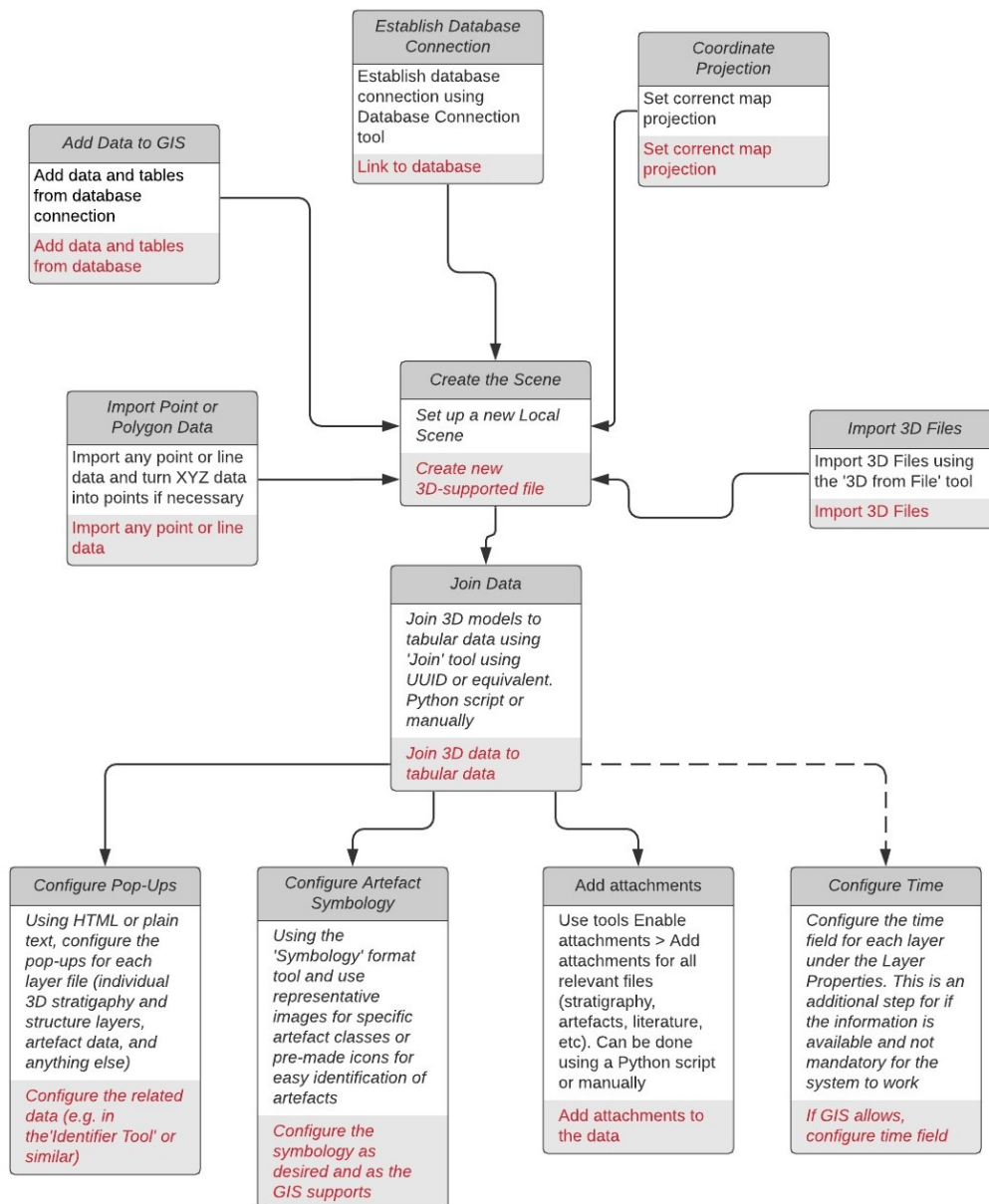


Figure 4-6 Flowchart showing an overview of the workflow described below. More general steps for future software in red. Non-mandatory steps shown with dashed line.

4.4.1 Setting Up the Local Scene

To begin, one must first create a 'Local Scene' in ArcGIS Pro and set the map projection to the standard used within the archaeological data. In the instance of the Keros Project, a local 'Keros Projection' was used within the Total Stations and later converted to WGS 84 UTM 35. The result was supplied by the site's architect as a Coordinate Systems File (PRJ) which could be loaded into the GIS.

Next, the project must be linked to the relevant SQL database. This can either be done through a local database file, a Database Connection using a server, or by connecting to a new Cloud Storage Connection. Once the database connection is established, all its files will be available to add to the Local Scene in the Catalog pane and can simply be drag-and-dropped into the map.

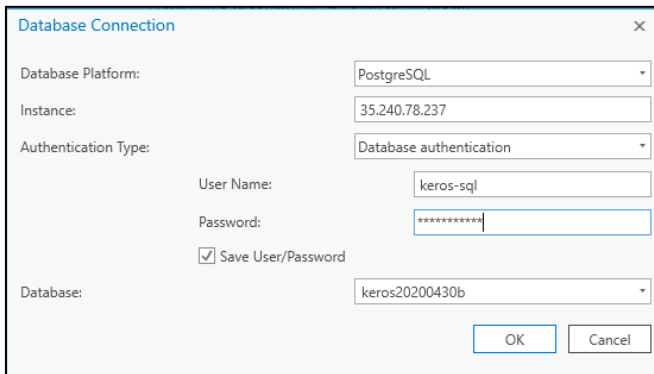


Figure 4-8 Database Connection tool prompts the log in information to the server

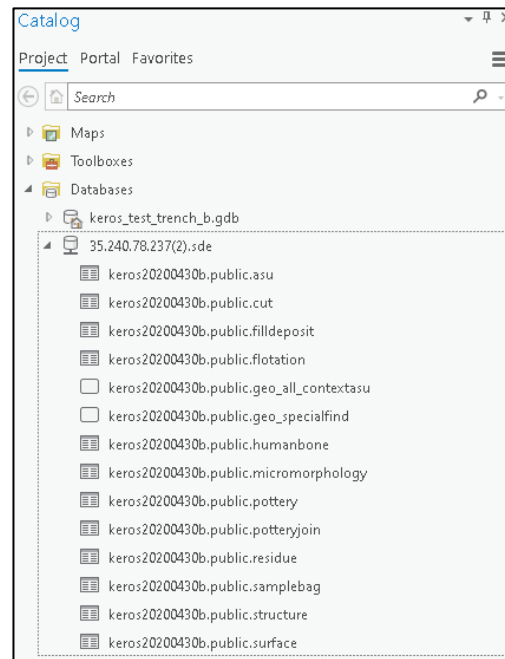


Figure 4-7 Databases connected to the GIS showing the IP address and tables/data available to add to the map as well as the internal geodatabase produced by ArcGIS Pro.

If there are any inconsistencies in categories that will make querying data more difficult, the ideal time to clean the data is now. This can be done easily using SQL in whichever database browser or system in place, especially using a ‘find and replace’ code, though can also be done within the GIS when viewing the table. For this project, I cleaned the Special Find data by making the ‘Title’ entry naming consistent. For example, some entries of an artefact were titled ‘Kouphonisi pebble’, while others ‘Koufonisi limestone pebble’. These inconsistencies were due to the way iDig forces users to input an artefact title each time an entry is made rather than having a drop-down selection to choose from. This can, of course, be done later if any continuity errors become noticeable, since the database in ArcGIS Pro is read and refreshed directly from the connected SQL database.

4.4.2 Importing Files

Importing the 3D files has been made far simpler in ArcGIS Pro than in its predecessor, ArcScene. ArcGIS Pro supports a number of different 3D file types including Collada, .ply, and .obj. Using the Geoprocessing tool ‘Import 3D from files’ allows the user to import either one file at a time or several which will be saved into a single table. For the stratigraphic files, the former option was chosen so that each layer could be toggled on and off without the need for a Definition Query. Meanwhile, architectural models were added in a single lot, meaning they could be queried based on phasing data and other points of interest more easily. In total, 291 3D models were imported into the GIS which contained the models of

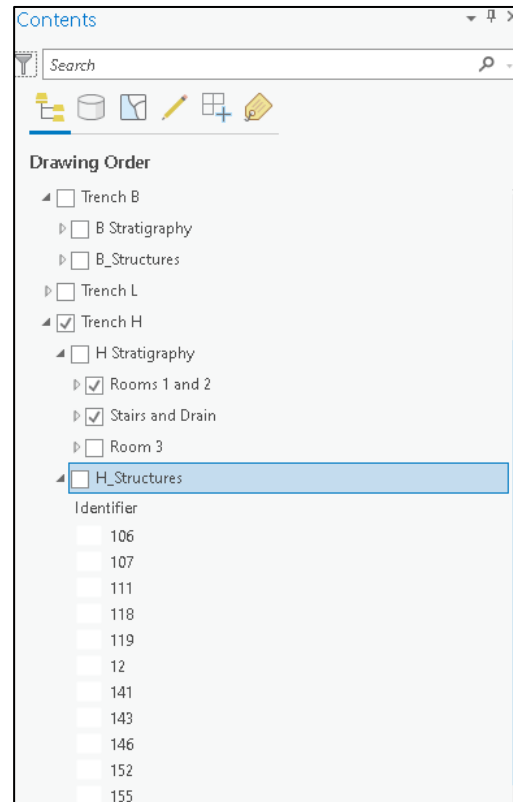


Figure 4-9 Contents pane showing the division of stratigraphy between rooms/spaces in trench H as well as the structures in a single grouped layer

the trenches at the end of the 2018 excavation, all structures as individual elements, and each stratigraphic context including fills and deposits, surfaces, and cuts. The Keros recording system included separating the site’s surface levels into two contexts, the surface make-up and the ‘event’ layer of the surface itself. It had been decided at the beginning of the project that only a single 3D model was necessary to record this as the two were at times indistinguishable and not always present. To compensate for this the 3D models of the surface make-up contexts are copies of

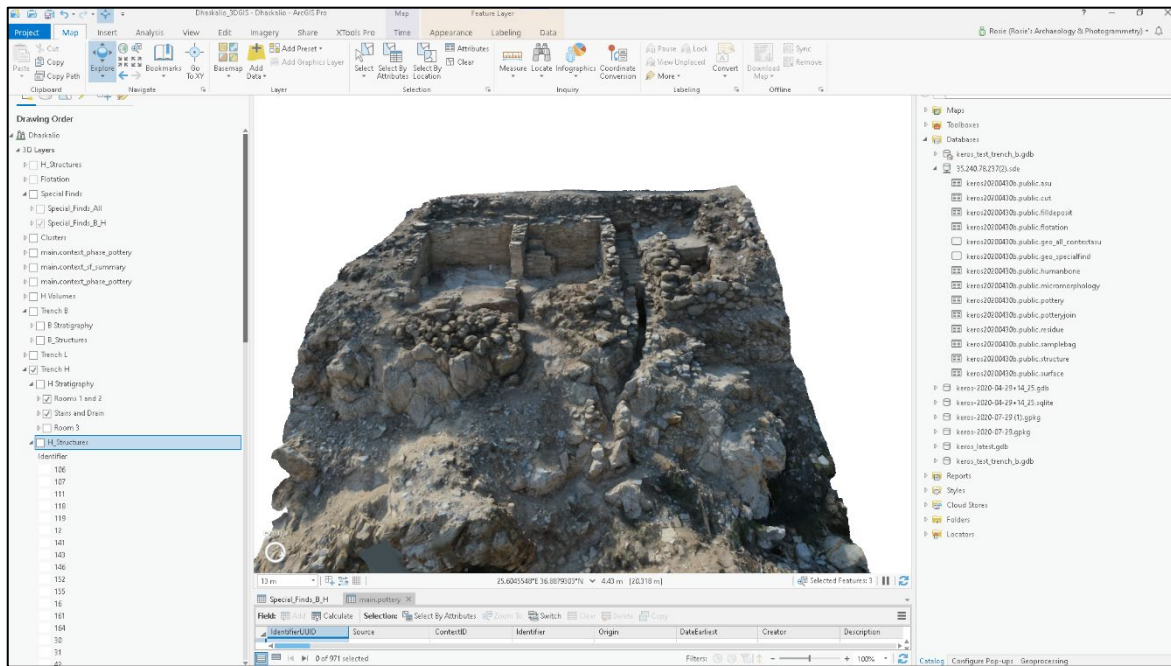


Figure 4-10 Trench H end of excavation 3D model imported into the GIS

those made for the surface event layer. A note of this was made in the ‘Description’ column where applicable. While it is impossible to turn a matrix into a single list, an effort was made to group the models by area/room and stratigraphic order based on the trench’s spatial matrix as provided by iDig. Figure 4.8 shows Trench H in the GIS with 3D models grouped by the rooms they belong to.

In this case, the Special Finds (SF) artefact data had already been created as georeferenced spatial data within the SQL database, where the GIS can read the spatial data for each entry and creates a point at the defined coordinate. If this has not been done, simply using the ‘add data by XY table’ tool can be used, assuming the XYZ points are known and can be found in the database. This will create a new 3D layer containing the artefact data. In total, 5827 artefact SF points were added to the GIS which was then reduced to the 1214 artefacts found in trenches B and H using a Definition Query to limit what was viewed.

4.4.3 Joining Data

Now that the excavation data and 3D files have been added to the GIS, the next crucial step is to join the 3D models to their respective field data. Assuming that the 3D model’s file name is identical to the identifier used within the database, this can be simple. However, if the filename differs the user will have to add an identification number to each 3D file’s attribute table that can be matched with the

excavation data. The latter was the required step in this project, and the Identifier UUID was added into each 3D context file's attribute table by copying the unique identifier from the excavation database tables. The join will copy the data from the 'Join' feature class (in this case, the relevant tables from the database) and add this data to the 'Target' feature class (the 3D files). The tool creates a match table which keeps track of each join, and is automatically saved to the project's internal geodatabase. To speed up the joining process, ArcGIS's python tool was used (see below), which enabled the ability to join several files at once. Joining can also be done through the geoprocessing toolbox but this must be done one-by-one which is less ideal for large quantities of files.

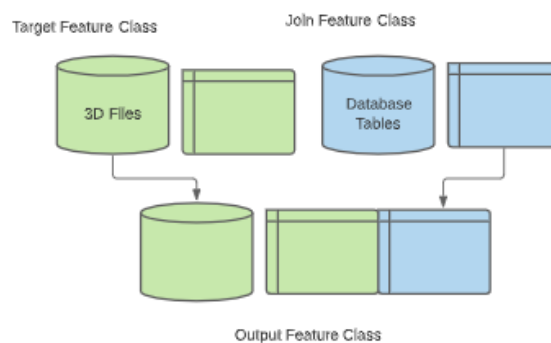


Figure 4-11 Joins in ArcGIS Pro to add excavation and specialist data to the 3D models

```
##Add join between layer and table##|
import arcpy
arcpy.env.workspace = "CURRENT"
structure_join_table = arcpy.AddJoin_management("Structures\\27", "IdentifierUUID", "main.structure", "IdentifierUUID")
arcpy.CopyFeatures_management(structure_join_table, "structurejoin") **optional
```

Figure 4-12 Example of script supplied by ESRI and modified by author to add join between a 3D object and the data table

4.4.4 Adding Attachments

In ArcGIS Pro attachments provide access to files associated with a layer's data. It provides a way to associate non-geographic data with geographic information. These are typically documents such as images, PDFs, HTML, or word documents. This tool was utilised to enable attachments on all of the project's data, including the 3D files. This was done on the SF points and 3D models where images were attached. As well as this, two additional tables were created in PostgreSQL to store the data for the related literature files as well as the field notes and any other PDF document relevant to the excavation. The literature table was simply imported from a CSV exported from a Zotero library into the PostgreSQL database and then added to the GIS (fig. 4.13). While it is possible to store PDF files within the PostgreSQL database itself, this can cause storage and memory issues especially with larger

PDFs, slowing down the database processing capabilities. Having the reference text data stored in the SQL database then imported into the GIS where attachments were made to the relevant entries means that the attached PDF and image files would be available and stored internally in ArcGIS Pro's internal geodatabase and not overrunning the PostgreSQL server.

C	Date	Author	Title	PublicationTitle	Issue	Volurr	Series
5	1964	Cann, J. R.; Renfrew,...	The Characterization of Obsidian and its application to th...	Proceedings of the Prehistoric Society	<Null>	30	<Null>
1	1965	Renfrew, Colin; Cann,...	Obsidian in the Aegean	The Annals of the British School at Athens	<Null>	60	<Null>
14	1967	Renfrew, C.	Cycladic Metallurgy and the Aegean Early Bronze Age	American Journal of Archaeology	1	71	<Null>
11	1968	Evans, J. D.; Renfrew,...	Excavations at Saliagos near Antiparos	<Null>	<Null>	<Null>	<Null>
15	1969	Renfrew, Colin	The Development and Chronology of the Early Cycladic Fi...	American Journal of Archaeology	1	73	<Null>
3	1972	Renfrew, Colin	The Emergence of Civilisation	<Null>	<Null>	<Null>	<Null>
6	2007	Renfrew, Colin; Phila...	Keros: Dhaskalio and Kavos, Early Cycladic Stronghold an...	The Annual of the British School at Athens	<Null>	102	<Null>
12	2007	Renfrew, Colin; Brodi...	Excavations at Phylakopi in Melos 1974-77	The British School at Athens. Supplementary Vo...	42	<Null>	<Null>
17	2007	<Null>	Keros, Dhaskalio Kavos: The Investigations of 1987-88	<Null>	<Null>	<Null>	<Null>
2	2008	Angelopoulou, Anast...	The 'Kastri Group': Evidence from Korfari ton Amygdalion...	Horizon: A colloquium on the prehistory of the...	<Null>	<Null>	<Null>
7	2009	Renfrew, Colin; Phila...	The Early Cycladic Settlement at Dhaskalio, Keros: Prelimi...	The Annual of the British School at Athens	<Null>	104	<Null>
8	2010	Renfrew, Colin	Contrasting Trajectories: Crete and the Cyclades During th...	British School at Athens Studies	<Null>	18	<Null>
9	2012	Renfrew, Colin; Boyd,...	The Oldest Maritime Sanctuary? Dating the Sanctuary at K...	Antiquity	331	86	<Null>
10	2013	<Null>	The Sanctuary on Keros and the Origins of Aegean Ritual...	<Null>	<Null>	<Null>	<Null>
13	2013	Kinnaird, T; Dixon, J	Sea-level change and the Early Bronze Age topography	The Settlement at Dhaskalio	<Null>	<Null>	The sanctuary on Kero...
16	2013	<Null>	The Settlement at Dhaskalio	<Null>	<Null>	1	The sanctuary on Kero...
18	2016	Sotirakopoulou, Pegg...	The Pottery from Dhaskalio: The Sanctuary on Keros and t...	<Null>	<Null>	4	The sanctuary on Kero...
19	2016	<Null>	The Pottery from Dhaskalio: The Sanctuary on Keros and t...	<Null>	<Null>	2	The sanctuary on Kero...
4	2017	<Null>	Early Cycladic Sculpture in Context	<Null>	<Null>	<Null>	<Null>

Figure 4-13 Table showing literature related to the excavation. This was imported via a CSV derived from a Zotero library.

Enabling attachments is a straightforward procedure which in this case was done using a python script to cut back on processing time, as multiple files and tables can be enabled concurrently (see fig. 4.14 below), though this can also be done using the geoprocessing toolbox. Once attachments had been enabled, the 'Add Attachments' tool was used to add file attachments. Attachments are added to the target dataset using a match table that can be used to dictate the path and name of the files that are to be added to a record. Attachments are copied internally to the geodatabase and do not affect the original file. The script will also create a match table. The tool will match the file names with the given input name within the selected folder. A second method can be done by simply right-clicking a record and selecting 'manage attachments' then drag-and-dropping the correct files to attach.

```
##Enable attachments ##
import arcpy, arcpy.EnableAttachments_management(r"D:\Photogrammetry\Keros_test_Trench_B\Keros_test_Trench_B.gdb\c116_Import3Dfiles")

##Add attachments script##
arcpy.AddAttachments_management(r"D:\Photogrammetry\Keros_test_Trench_B\Keros_test_Trench_B.gdb\geo_specialfind_XYTableToPoint", "Identifier",
r"D:\Photogrammetry\Keros_test_Trench_B\Keros_test_Trench_B.gdb\geo_specialfind_XYTableToPoint_ATTACH", "Identifier", "ATT_NAME", r"D:\Keros Photogram\TrBSF")
```

Figure 4-14 Example of script supplied by ESRI and modified by author to enable and add attachments to layers.

Both of these methods were employed, each with its own benefits. The former is useful if the attachments have standardised names, such as sequential photographs, and the latter was found more efficient when multiple file types were attached (such as PDFs and JPGs) as well as for adding files whose names were not standardised.

4.4.5 Configuring Pop-Ups

The pop-up functionality of ArcGIS Pro is extremely useful for exploring data in three dimensions as they allow one to have a summary of a file within the GIS environment when it is clicked. The standard format for a pop-up only includes

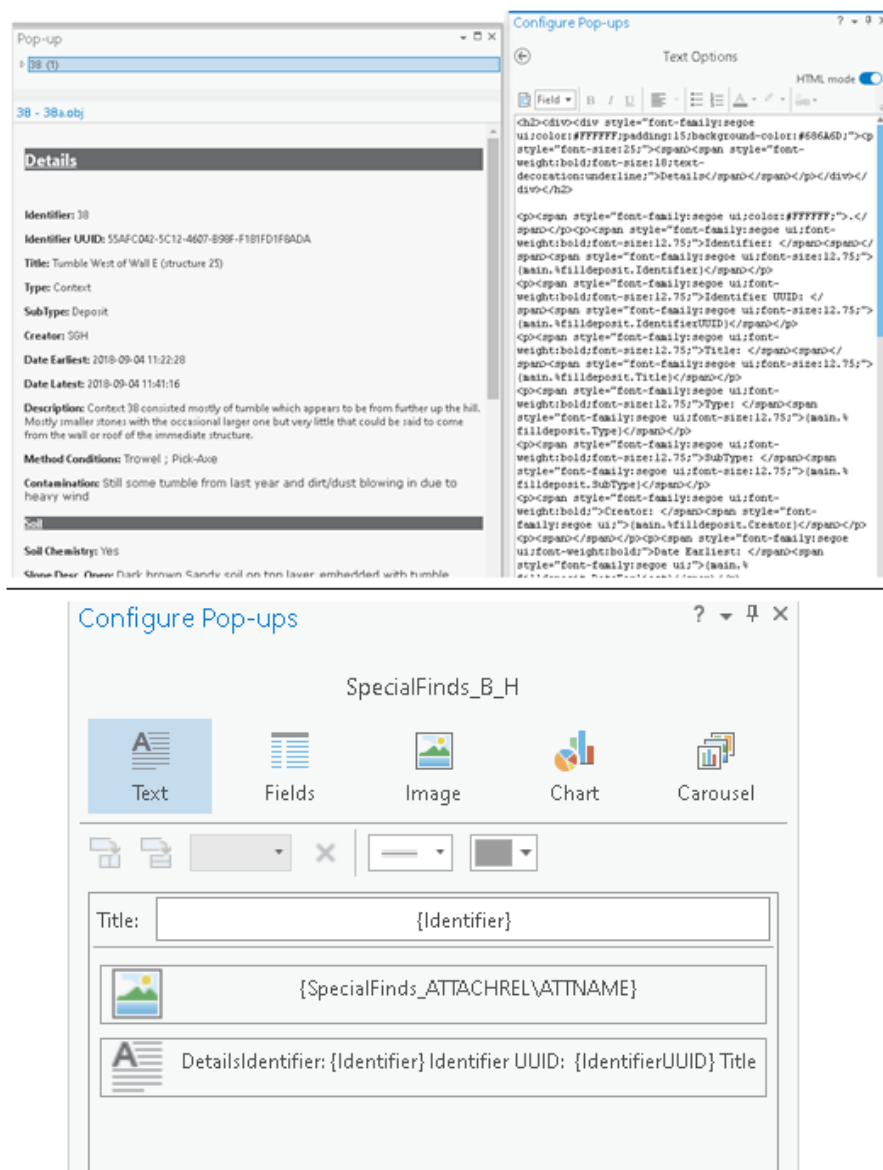


Figure 4-15 Pop-up (top left) and customised HTML code (top right) and the 'Configure Pop-ups' pane (bottom).

a dump of all fields from within the layer's attribute table. To make the experience more user-friendly and readable the pop-ups were configured using HTML. This meant that only the data useful to the user would be seen (fig. 4.15). Pop-ups can also display the images that are attached to a file, which can be turned on in the main 'Configure Pop-ups' pane.

4.4.6 Symbology and Time

In order to make the SF point data more easily identifiable as artefacts, the symbology was configured to use a representative image of an artefact type as its marker. To do so, in the symbology settings of the SF layer, the symbology was set to use unique values using the 'Title' field. This divided the symbols into 43 different values based on artefact type. Each value was modified to use a photograph as its marker based on a random example of the type in the SF photography. An example of this can be seen in fig. 4.16 where a photograph of a schematic marble figurine found in the excavation is used to represent all artefacts classified as 'Marble Figurine'. The aim of this step is to allow for better visual analysis when exploring the data in 3D by having an idea of what artefact types are present and where they are located in the site.

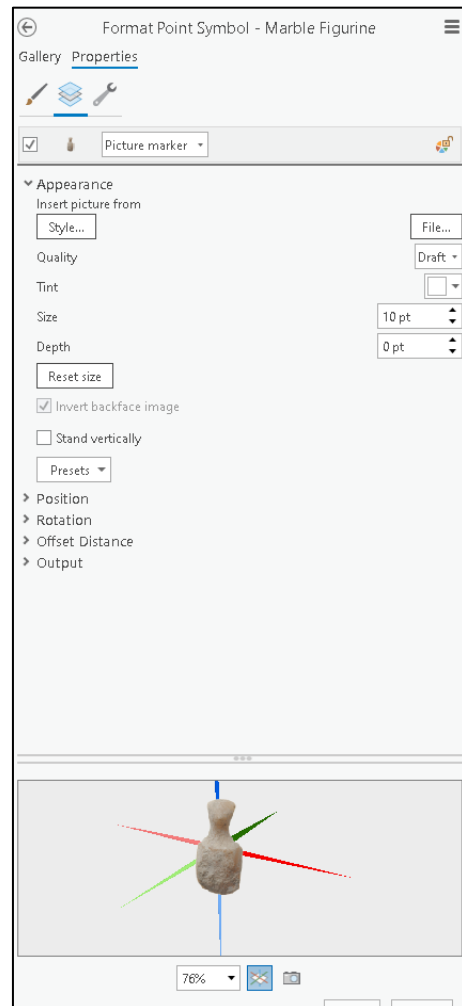


Figure 4-16 Formatting the symbology of artefacts to represent their artefact type

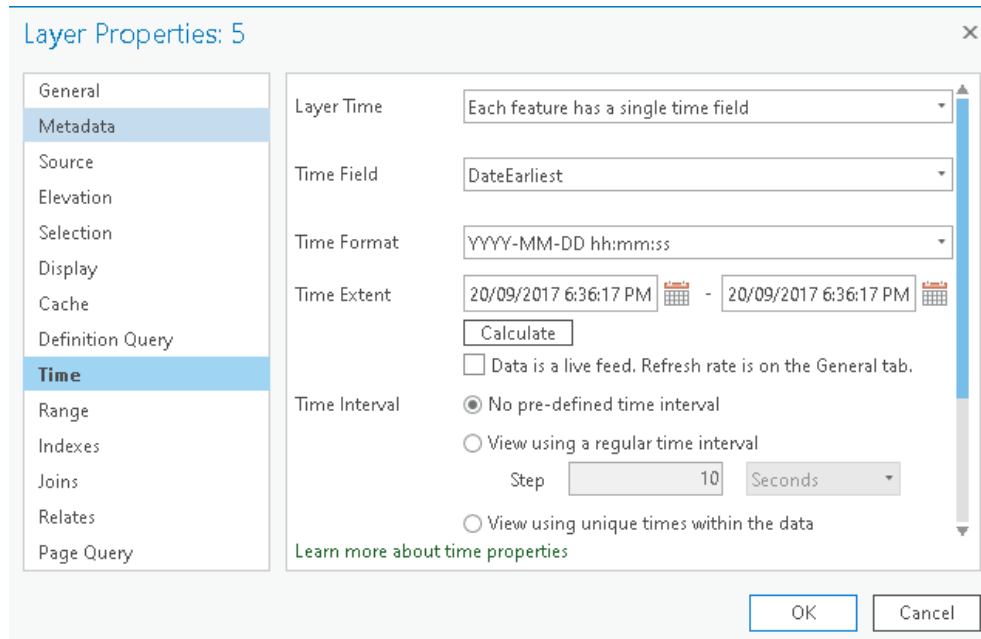


Figure 4-17 Layer properties of a context, turning on 'time' component.

The final step in this process is to configure time into the project. This is a useful tool for visualising temporal data in the GIS. When a record was created in iDig during the excavation, it was given a timestamp. This can be recognised in the layer's properties under 'Time', which will automatically be read when the function 'Layer Time' is turned on (fig. 4.17). This was done for each the Special Find data and the 3D stratigraphic model data. Under the 'Time' tab in the GIS, the time slider can be used to toggle on and off layers and features based on their time value. Figure 4.18 explains how the time slider works within the GIS environment.

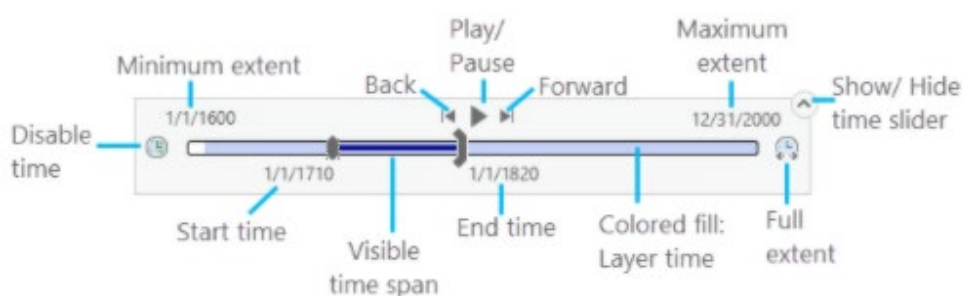


Figure 4-18 Example of how the time slider works (from Esri, <https://pro.arcgis.com/en/pro-app/help/mapping/time/visualize-temporal-data-using-the-time-slider.htm>)

4.5 REBUILDING THE WORKFLOW IN OTHER SOFTWARE

As has been made clear, this workflow was created using the proprietary software ArcGIS Pro with the intention for it to be applicable to open-source software in the future. While not all features (such as the time-slider) may be available in future FOSS software, it remains an additional step. The steps integral to the structure of this workflow are the ability to join tables and features, add attachment files, and easily access data via the pop-up system. All of these features are already available in open-source GIS programs and are common in 2D GIS in general. QGIS, for example, has an ‘identify features’ tool similar to ArcGIS Pro’s pop-ups, supports attachments of images and files, and maintains joins between different data. In theory, once GIS alternatives begin to support true 3D GIS and 3D mesh files, these same steps could be followed to produce a similar result. The outcome of the above methods was a fully integrated, living, three-dimensional database that could be used to analyse and explore the site both visually and statistically. The various facets of use for this system will be outlined in the following chapter, 5.

5 RESULTING PRACTICAL APPLICATIONS

In this chapter I will outline the results of this project using practical applications as examples. The first part will consist of a discussion of the practical applications of this integrated system, with screenshots taken from the ArcGIS Pro environment to illustrate the varied functions and facets of data exploration and manipulation described within chapter 4. The second part of this chapter will be composed of a case study using the Special Find (SF) artefact data and a statistical clustering analysis to exemplify the analytical capabilities of this system. This

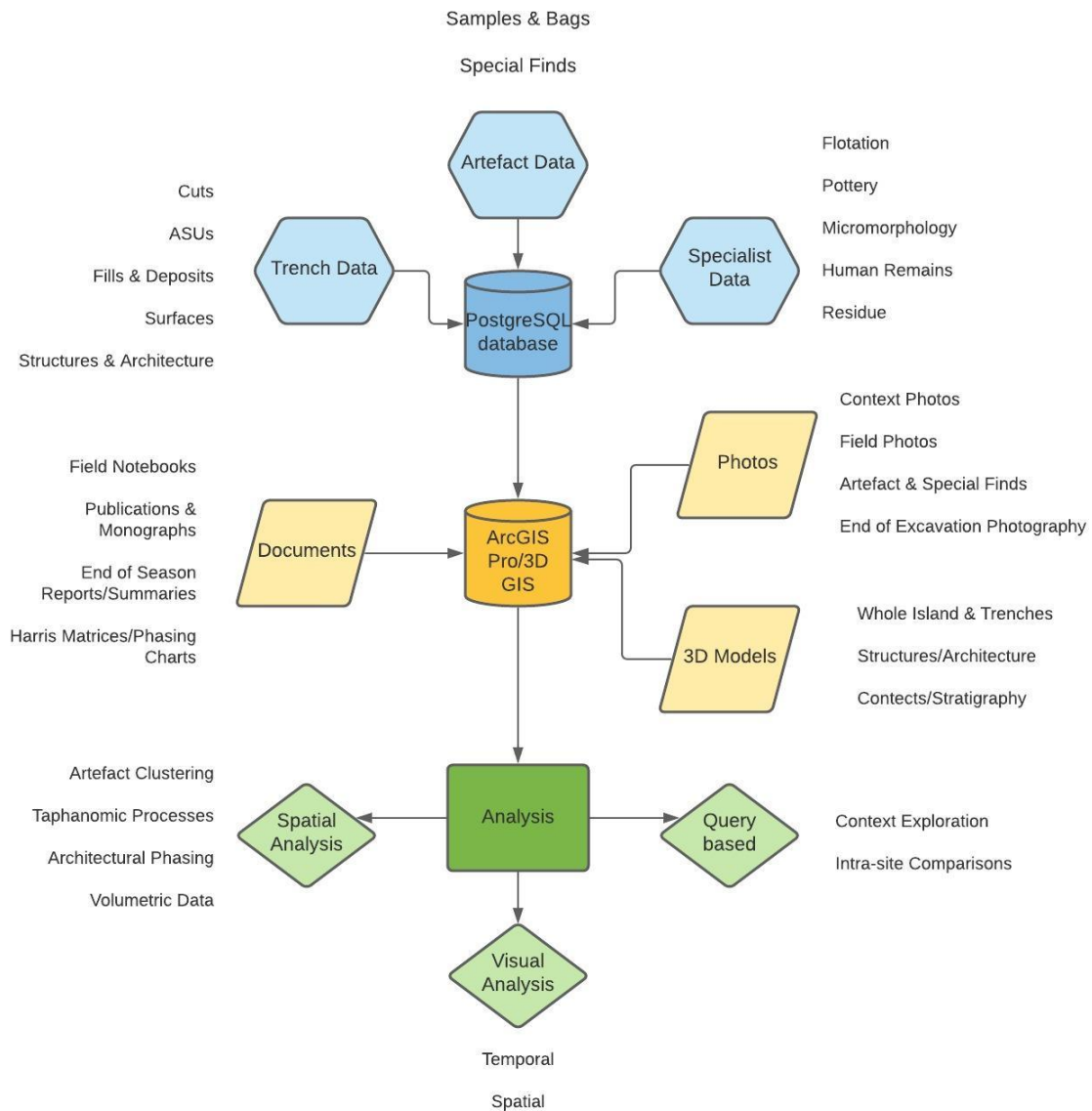


Figure 5-1 Flowchart showing the various inputs and outputs of the proposed system.

chapter will illustrate a ‘living’, fully integrated 3D GIS database. The various inputs and their outputs of this system are summarised in fig. 5.1, above

5.1 TRENCH DATA AND VISUAL ANALYSES

Data entry and data visualisation have been staples of GIS for decades. This section demonstrates the system’s preservation of complex three-dimensional data and its ability to seamlessly join them to relational trench data. It will demonstrate the function of running queries and filters, making this a smooth and simple process, while the personalised pop-ups allow for simple identification of features.

5.1.1 Integration of Site Data

An important component of this project has been to utilise an SQL database as the “back end” while using the 3D GIS as a user-friendly “front end”. Within this system such integration is seamless: data can be edited in an outside software (in this case, PostgreSQL Admin Manager tool) and the edit will immediately be visible within the GIS once the database connection has been refreshed. Figure 5.2 below shows this by editing the phrase “*TEST*” into context 3 from trench B in the Postgres Admin Manager (top), and the way this edit is reflected in the GIS environment (bottom) in both the table data and the linked pop-up data. The reverse is also true, where editing the data within the 3D GIS environment will write the changes to the SQL database. Furthermore, having the database hosted on a server means that both the database can be open, used, and modified by several users at once. This is ideal for an archaeological project where specialists, supervisors, and directors live in different regions and may need access to edits or changes made to the data by one another at once.

Dashboard Properties SQL Statistics Dependencies Dependents public.filldeposit/keros20200430b/keros-sql@keros-sql

public.filldeposit/keros20200430b/keros-sql@keros-sql

Query Editor Query History

```

1 SELECT * FROM public.filldeposit
2 ORDER BY "Source" ASC

```

Data Output Explain Messages Notifications

	Identifier [PK] character varying	Source character varying	Type character varying	SubType character varying	Identifier character varying	Title character varying
210	67197D88-B5AC-4D2B-AA...	D19-A	Context	Cleaning	137	Section Cleaning in central room (2016 'structure' 5D)
211	09B662D1-4D0E-4D1E-8F...	D19-A	Context	Cleaning	135	Backfill Cleaning 2018 (whale of Trench A)
212	67BBF43D-0586-4432-B7E...	D19-A	Context	Deposit	134	Lower collapse (possibly 103, but looks different and is below une...
213	49E7D39A-063B-4D91-B7...	D19-B	Context	Cleaning	120	Cleaning 2019 study season
214	3320B062-0419-4D3C-94...	D19-B	Context	Deposit	1	Surface clearance
215	38CDDFA0-B36D-414E-9B...	D19-B	Context	Deposit	2	Topsoil
216	344DA8C5-51DC-470C-93...	D19-B	Context	Deposit	7	Tumble
217	0988B98C-667D-42E8-AC...	D19-B	Context	Deposit	9	Make up of Surface 5
218	8CC0CC8-F4AF-4459-96...	D19-B	Context	Deposit	3	Mixed subsoil and tumble deposit *test*
219	ADDE4D48-1FAD-4AB8-B8...	D19-B	Context	Deposit	8	Collapse from wall A (context 4) overlying surface 5
220	375C5062-78BE-41B8-936...	D19-B	Context	Deposit	12	Make-up of surface 11
221	528C421D-9BAD-43CB-AA...	D19-B	Context	Deposit	13	Collapse deposit within possible 'room' east of Wall B (structure 14)
222	BEF4B4A4-8F77-4E2F-A9...	D19-B	Context	Deposit	17	Deposit in between bedrock underlying 12.

Contents

Drawing Order

- Dhaskalio
 - 3D Layers
 - Special Finds
 - Special_Finds_All
 - Special_Finds_B_H
 - Clusters
 - H Volumes
 - Trench B
 - B Stratigraphy
 - 2
 - 3
 - 8
 - 5
 - 6
 - 9
 - 11
 - 12
 - 13
 - 7
 - 18
 - 57
 - 60
 - 41
 - 58
 - 61
 - 83
 - 38

Pop-up

4 3 (1)

3 - 3a.obj

Details

Identifier: 3

Identifier UUID: 8CC0CC8-F4AF-4459-9659-548E536F7E2

Title: Mixed subsoil and tumble deposit *TEST*

Type: Context

Subtype: Deposit

Creator: CD

Date Earliest: 2017-09-12 05:07:20

Date Latest: 2017-09-22 05:54:45

Description: Layer of mid-dark brown subsoil with frequent large stone (boulders) inclusions, many of which are worked stones from collapsed walls (come probably from terracing/wall A further up/slope at the south side of Trench B). This deposit is firmer/more compact than the overlying topsoil. It is also coarser, with tiny stone inclusions. There are more sandy patches within the subsoil, and it is slightly mixed, probably because it has formed over several hundred/ or a few thousand years?

Method Conditions: Trowel ; Hand Pick ; Pick-Axe

Type	SubType	Ident	Title	DateEarl
Context	Fill	6	Expansion of TT 05 on the South, level 1	2017-09-2
Context	Fill	7	Expansion of TT 05 on the South, level 2	2017-09-2
Context	Fill	8	Fill South of the Possible Structure	2017-09-2
Context	Fill	9	Cobbly Fill West of Wall B	2017-09-2
Context	Fill	10	Fill Between Rocks of Possible Structure	2017-09-2
Context	Fill	11	Cobbly Fill South of Feature/ Possible Struct...	2017-09-2
Context	Cleaning	120	Cleaning 2019 study season	2019-09-1
Context	Deposit	2	Topsoil	2017-09-1
Context	Deposit	3	Mixed subsoil and tumble deposit *TEST*	2017-09-1
Context	Deposit	7	Tumble	2017-09-2
Context	Deposit	8	Collapse from wall A (context 4) overlying ...	2017-09-2
Context	Deposit	9	Make up of Surface 5	2017-09-2
Context	Deposit	12	Make-up of surface 11	2017-09-2
Context	Deposit	13	Deposit in between bedrock underlying 12.	2017-09-2
Context	Deposit	17	Collapse deposit within possible 'room' east...	2017-10-1
Context	Deposit	18	Tumble in nw part of trench	2017-10-1
Context	Deposit	19	Tumble deposit within walls in northeast cor...	2017-10-1
Context	Deposit	20	'Packing' or Deposit in between the flattene...	2017-10-1
Context	Deposit	21	Tumble/collapse in east side of trench.	2017-10-1
Context	Deposit	22	Tumble within northeast room	2017-10-1
Context	Deposit	35	CLEANING LAYER start of 2018 season	2018-09-1

Figure 5-2 Edit made externally in database using PG Admin (top) immediately reflected in ArcGIS Pro environment (bottom)

Immediate access to the attached literature can be seen in fig. 5.3, where opening the attachments of an entry in the literature table will open the file in the default PDF or word-processing software. This same function applies to all digitised field notebooks, end of season reports and trench summaries, as well as PDFs containing Harris Matrices and phasing data. See supplementary material Video 1 for a demonstration on accessing relevant PDF files within this system.

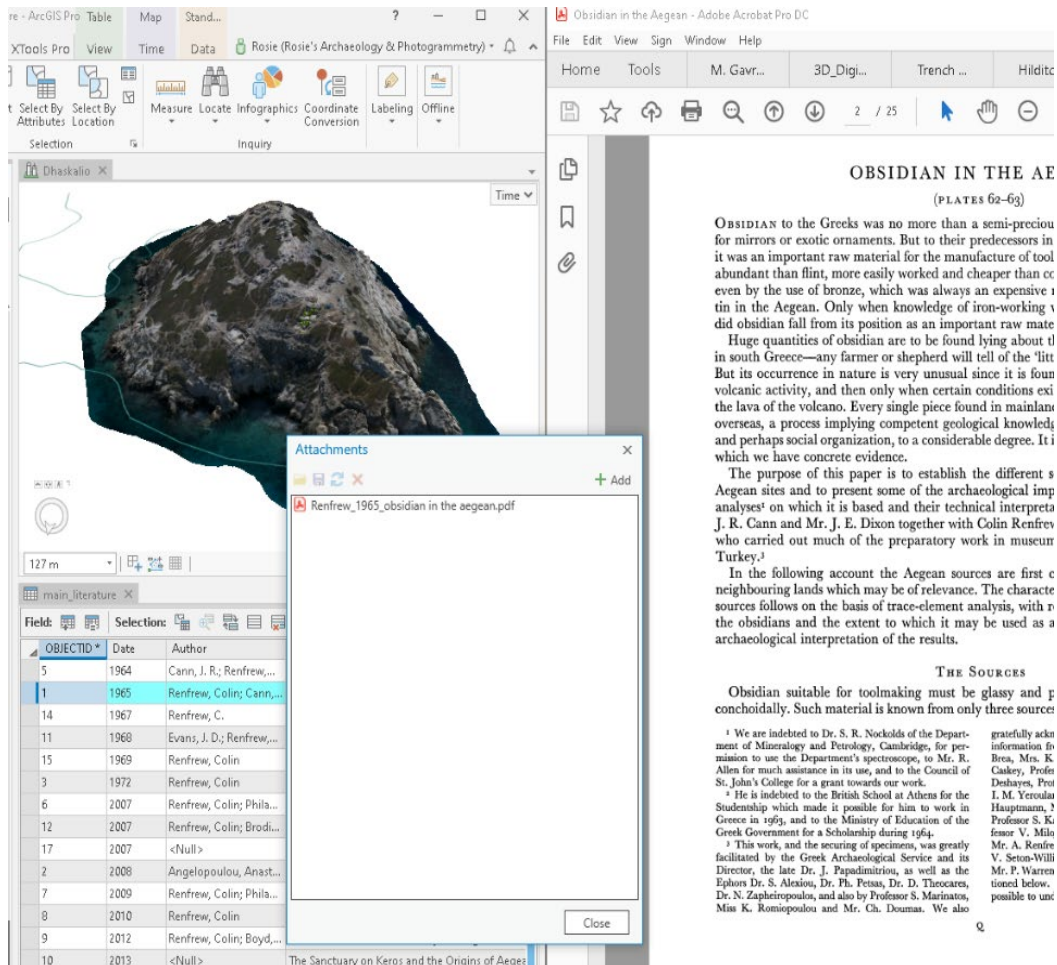


Figure 5-3 Accessing file attachments stored in the GIS. A journal article is opened in the default PDF viewer by double-clicking the file in the GIS.

Standard Polyline and Polygon data can be viewed in 3D using the site's DEM, but can also be used in its original 2D format if desired. This enables the user to access different data types that may have been created using standard GIS, and opens the potential to view plans from older excavations where Z coordinates have not been taken in a projected 3D environment. Figure 5.3 illustrates the use of architectural plans of the site made in CAD by the site's architect projected in both 3D and their original 2D format. As noted by both González-Tennant (2009) Jensen(a, 2018), a prominent issue for archaeologists collecting spatial data is that often they are not integrated with non-spatial data. This not only stifles the development of standards of digital recording, but also drives a wedge between data types, discouraging researchers from exploring all of the datasets available. This

workflow aims to mitigate this issue by bringing all available data types together to be accessed in a single holistic environment.

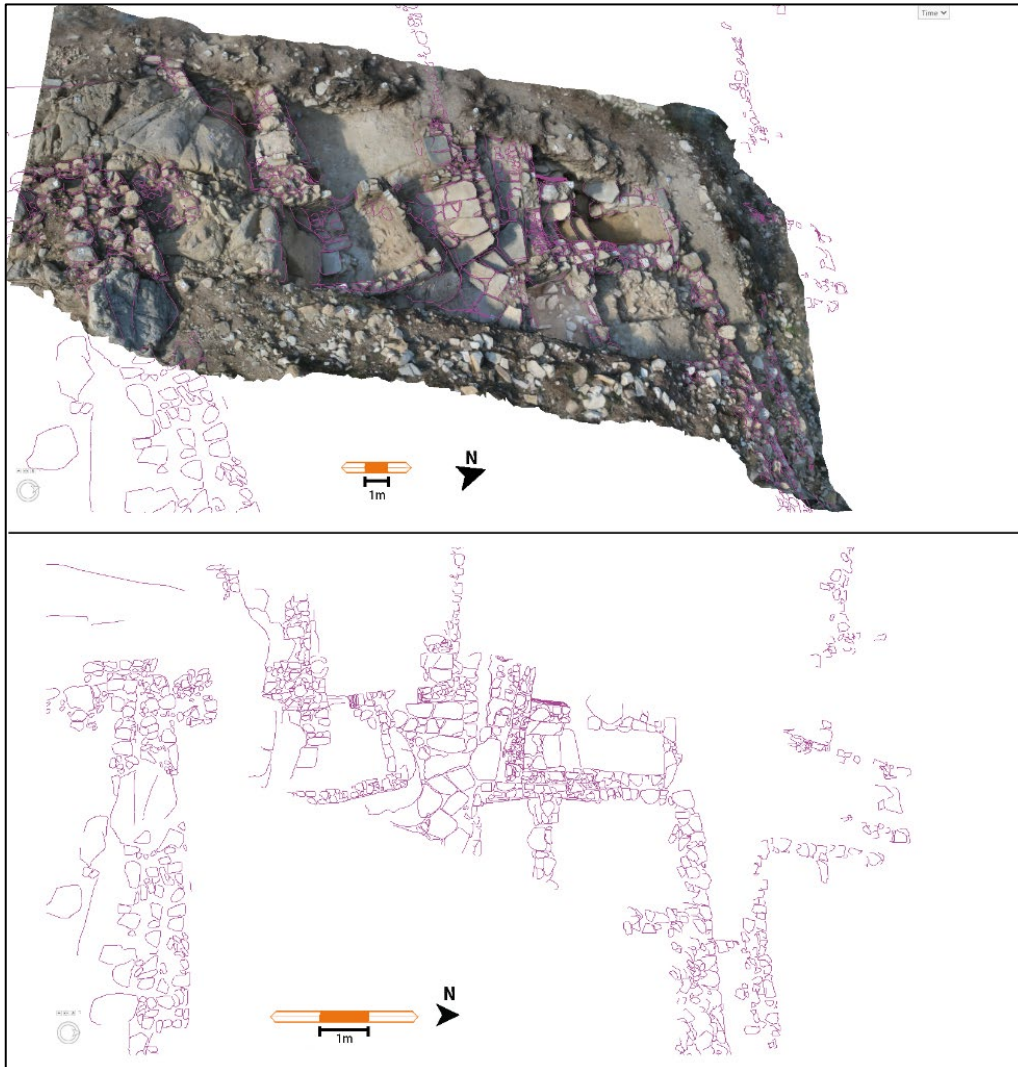


Figure 5-4 Polyline and Polygon data can be viewed either in 3D (top) or planar 2D (bottom)

5.1.2 3D Files and Components

Moving on to the three-dimensional files, the 3D photogrammetric model created for each context is accessible through the Contents pane and can easily be switched on and off or filtered for a specific file (fig. 5.5). As well as this basic filtering, Definition Queries can be run on point data such as the Special Finds (SF) and 3D models such as the structures so one can handle specific parts of the data.

The SF artefact data is also visible and easy to manipulate. Figure 5.6 shows all of the SF artefacts in trench H with none of the stratigraphic layers on, the custom symbology allowing for one to easily recognise artefact types by their appearance. The SFs are placed in their measured XYZ positions from their excavation within the trench. Moreover, SFs can be queried easily based on whatever parameters the user desired, such as to show only finds from a specific context or material class. This is demonstrated in the supplementary material Video 2. By clicking on any artefact, a pop-up (fig. 5.7) appears which not only gives the details of the item as found in the excavation database, but also provides thumbnails of photographs taken of the artefact which had been attached to the layer. When this thumbnail is clicked, the image will be opened in full size using the computer's default photo preview software. This provides the user with seamless interaction with the artefact and adds context to the data by seeing it 'in (digital) situ'. Similarly, the same system is in place for the multipatch photogrammetric files such as the architectural remains and the contexts. When a part of the trench is clicked, a query will automatically run, and the pop-up will open (see Video 3). When two or more features are in the same area, the information can easily be toggled between the features. Figure 5.8 shows this using a drain structure in trench H.

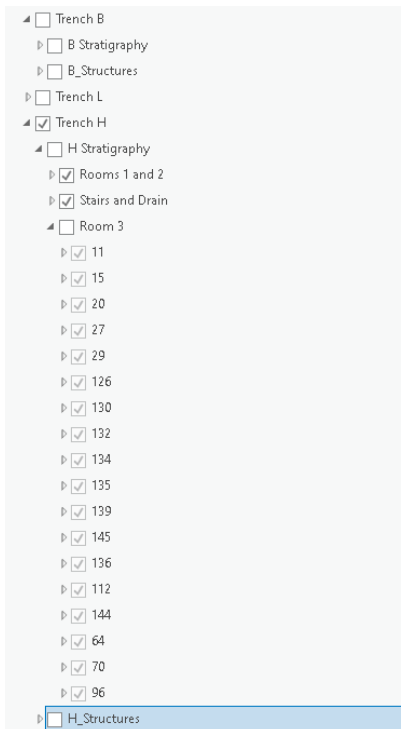


Figure 5-5 Contents pane showing different 3D models of contexts from Trench H



Figure 5-6 Trench H, showing all Special Find points in the GIS

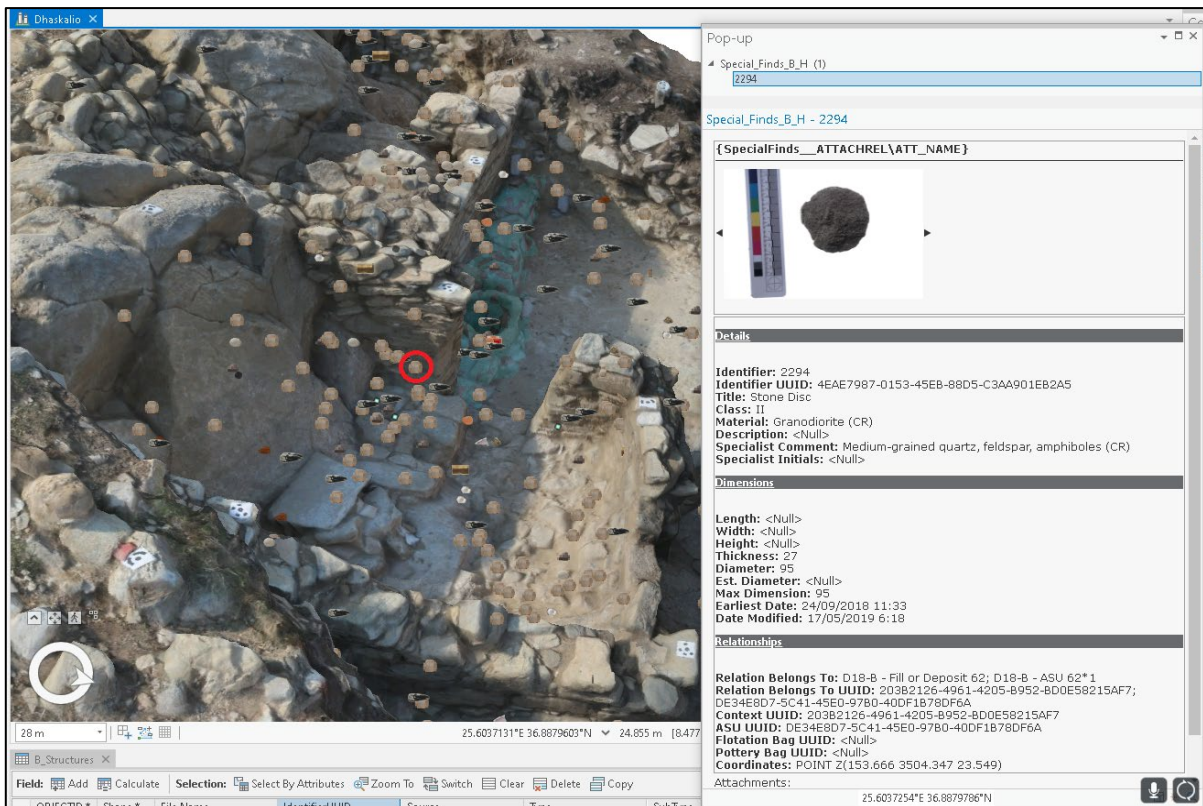


Figure 5-7 Trench B, Special Find pop-up with the SF clicked on circled in red

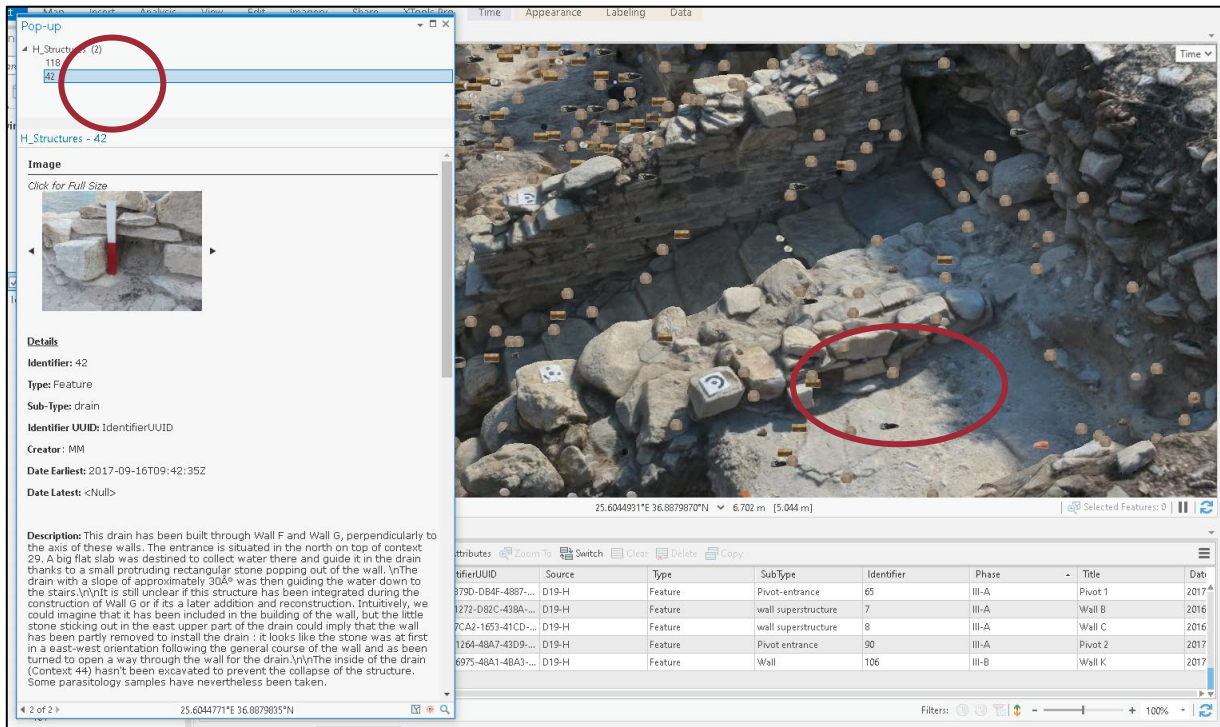


Figure 5-8 Pop up showing details and photographs of structure 42, a drain (circled). Other nearby objects can be toggled at top of pop-up (circled on pup-up)

The photogrammetric models of each context can be identified similarly to the artefact and architectural data by clicking and viewing the pop-up. Further data exploration can be done by way of queries and the ‘Exploratory Analysis’ tool provided in ArcGIS Pro’s 3D Analyst toolbox. This tool creates a cross-section of the scene from the user’s specifications, though it should be noted that this is not a cross-section in the usual archaeological term as it can be placed anywhere within the trench. This allows one to view the stratigraphic sequence in any area of the trench and at any angle as it is not restricted to the baulk or trench edge as in standard stratigraphic recording, but rather is an accurate representation of the topography of the context. Lines show the division between layers. Clicking the layer opens pop-up information which can easily be toggled between those nearby and includes the ability to flash the feature to show its location and extent. These features are shown in figure 5.9. It should be noted that this is viewed in three-



Figure 5-9 Using Exploratory Analysis tool to view a cross-section of the stratigraphic sequence in Room 3 of Trench H

dimensions with perspective, which must be taken into account. This is different from traditional 2D representations of strata, however any 2D representations can be added to the dataset by adding the files as attachments, which gives one the ability to cross-reference easily.

Furthermore, it is possible to run queries in the data which allows for a more comprehensive analysis of the above-described artefacts and stratigraphic data. Figure 5.10 shows a 'Definition Query' written to display the SF data of only artefacts found in context 116 and its associated subunits (ASUs). While this example uses written SQL, the software also provides a simple 'Query Builder' where one can use drop-down boxes to fill in the query. Figure 5.11 shows the

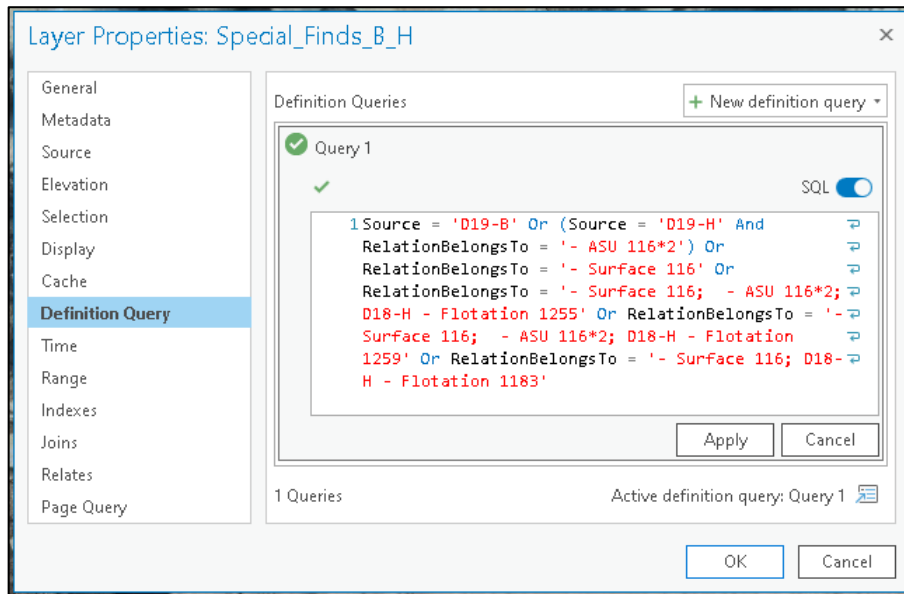


Figure 5-10 Definition Query used to filter layers to context 116, trench H



Figure 5-11 Artefacts from Surface 116 showing locations within stratigraphy using the Exploratory Analysis tool

combination of the previously discussed tools to view only the artefacts from 116 in situ within the stratigraphic sequence, with the top and bottom models of 116

turned on and using the ‘Exploratory Analysis’ tool to view them in section. The section was taken at the eastern limit of layer 116 to show all of the artefacts in the sequence. See supplementary material Video 4 for an example of this process. It is easy to imagine that the utilisation of these tools may aid in answering questions about the use of spaces, artefact use and placement, and how the morphology of occupation phases built up over time.

Architectural phasing data from across the island can also be interacted with in three dimensions. Here, in fig. 5.12, the 3D wall models across B and H are coloured by a shared site symbology according to the site phasing data. To further explore this data, one could simply add a ‘Definition Query’ to the ‘Structures’ data so only walls from a specific phase of the site would be visible. A benefit of this is the ease with which one can pan across the site to compare the locations and details

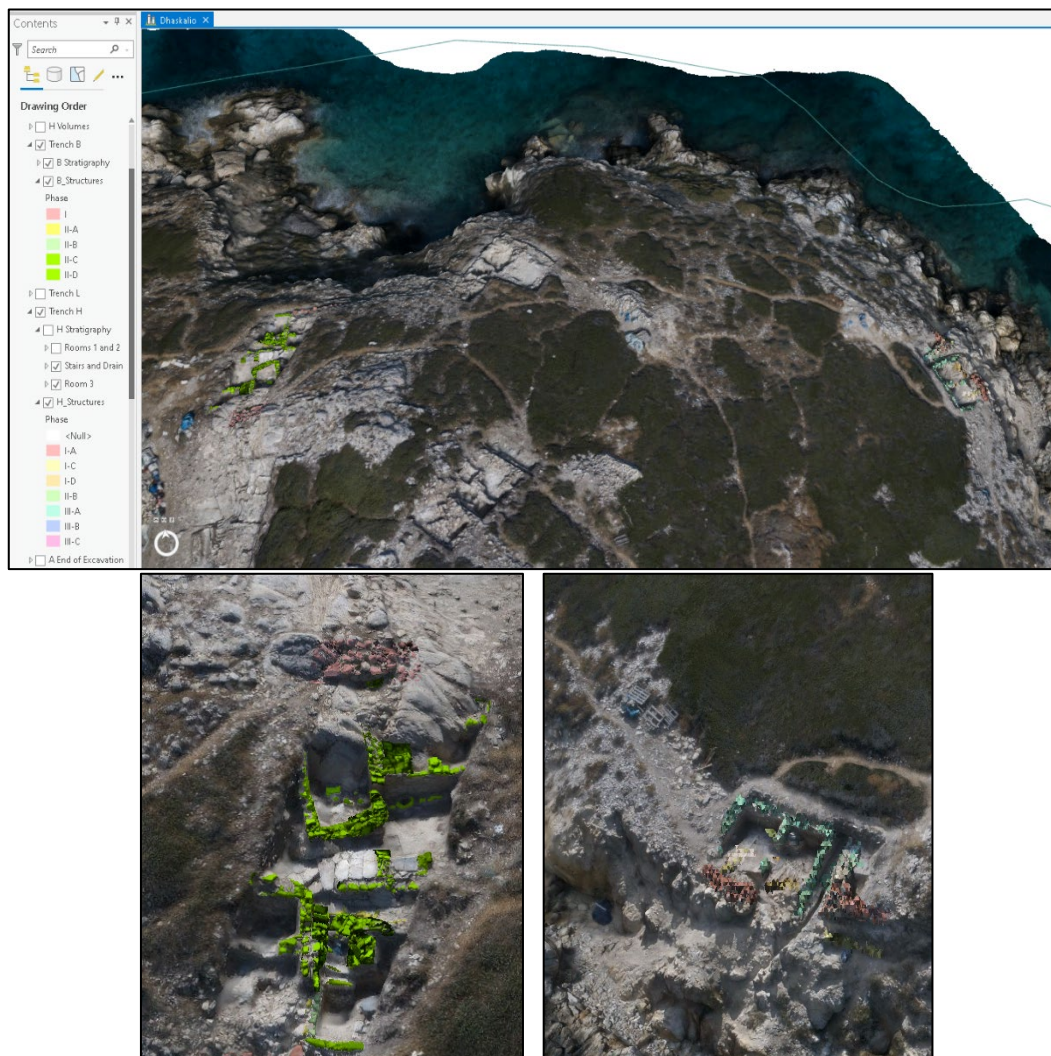


Figure 5-12 Colouring architecture by phasing. Dhaskalio island (top), Trench B (bottom left) and Trench H (bottom right).

of the walls, to get a better idea of how the site may have looked and what areas were active in a particular phase.

Fig. 5.13 shows the reliability of the ‘Measure Distance’ tool being utilised for measuring architectural remains, with an example from trench B. The tool calculates the length as 2.8 m which is the same measurement taken by the excavators in the field of the maximum length of the structure. Heights can also be measured, meaning that where walls are varied in height due to the number of courses preserved or the topography or height data may be missing, they can be better recorded in post-excavation by using the 3D GIS.

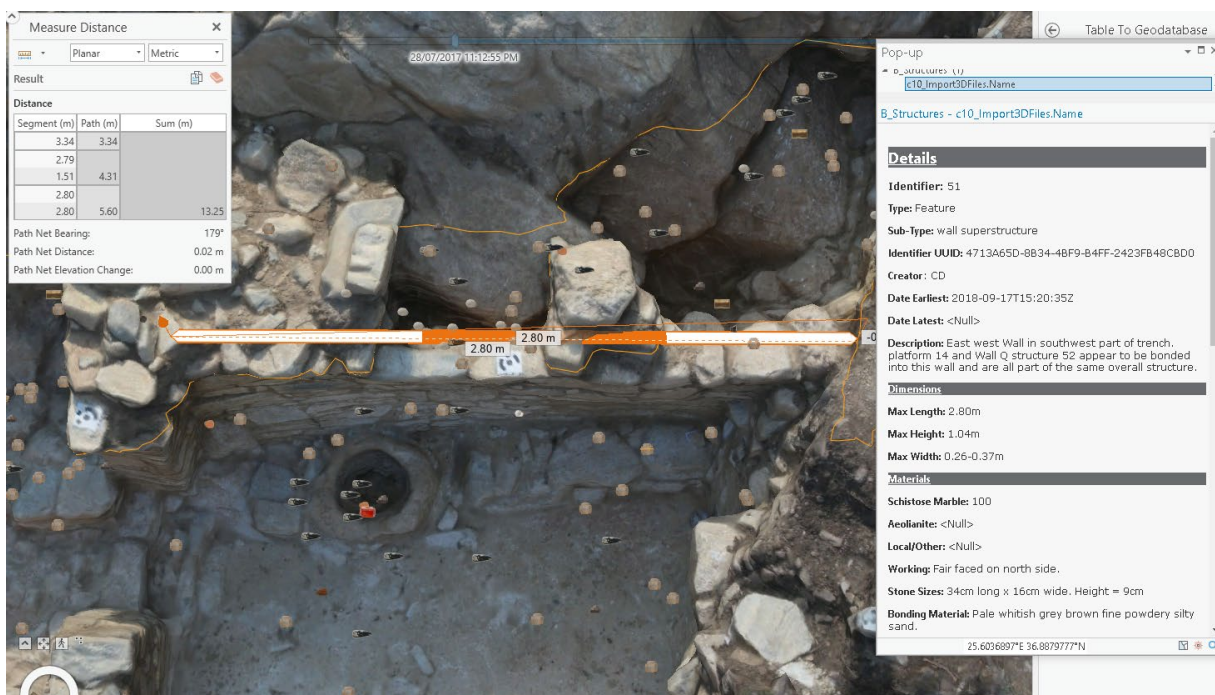


Figure 5-13 Using 'Measure Distance' tool to measure the length of wall 52 in trench B, compared with measurements taken in the field as seen in the pop-up

5.1.3 Volumetric Data

The use of photogrammetric models to create solid volumetric models has been a much-desired output (Gavryushkina, 2018; Katsianis, 2020). The 3D GIS is certainly capable of supporting three-dimensional volumes, and there is a way of recreating estimates of a context's volume in the GIS by using the ‘Minimum Bounding’ tool. However, as noted by Gavryushkina (2018) this method can exaggerate the area, meaning the volume should only be taken as a rough estimation. Regardless, for some archaeological purposes an estimate may be all

that is required beyond more precise research questions, such as an estimate for the volume of soil removed from a trench, or for comparison between the volume of layers. More specific questions will likely require better made volumetric models. Figure 5.14 illustrates a volumetric model of surface 116 in trench H made in ArcGIS Pro using the system outlined by Gavryushkina (2018) by using the 'Minimum Bounding Volume' tool, with the artefacts associated with the stratigraphic layer visible within it.

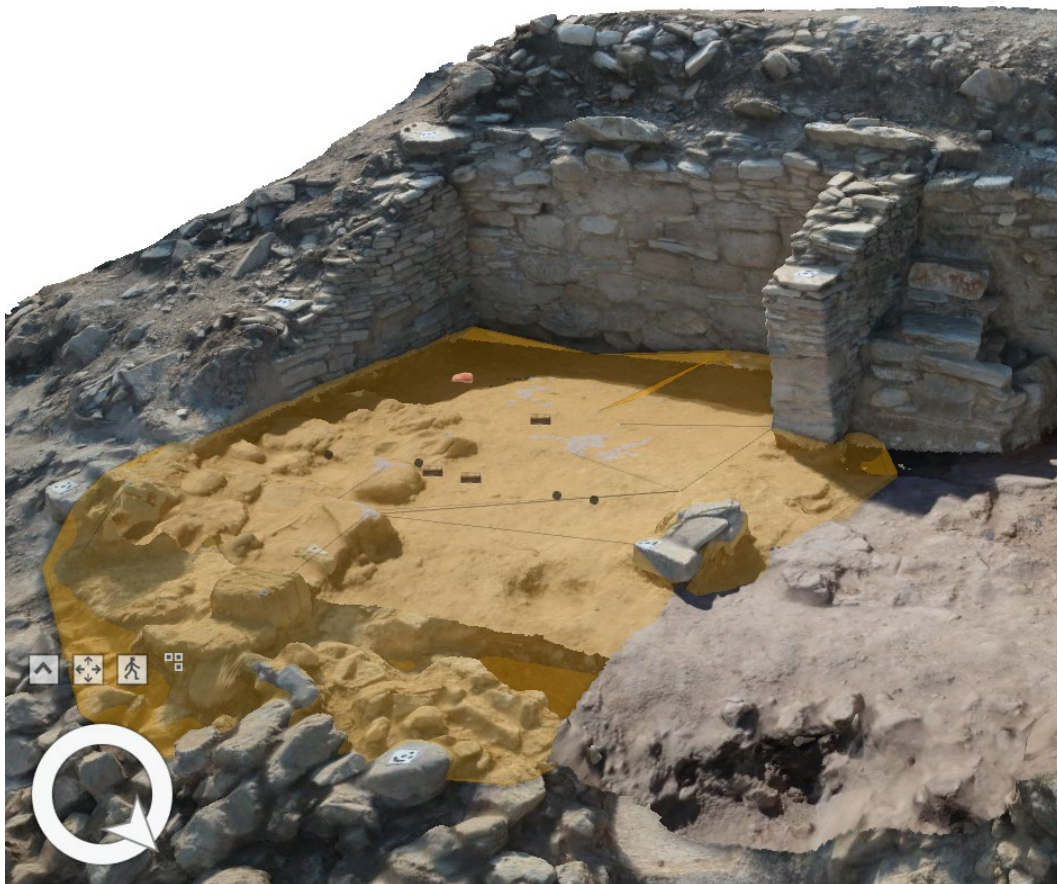


Figure 5-14 Estimated volume of surface 116 in trench H using 'Estimated Bounding Volume' tool, with only SF artefacts from 116 visible.

5.1.4 Exploring Time

Another result of this system is the ability to conduct investigations using time. Both artefacts and stratigraphic layers can be toggled on and off based on the time the iDig entry was created in the field at the time of their excavation. Utilising the temporal tools within ArcGIS Pro is an interesting component of this system and an example of how it works can be found in supplementary material Video 5. This allows one to reconstruct how the site was excavated as it was interpreted by

the excavators, which adds elements of reflexivity to the excavation process itself. This may aid researchers for better planning in future projects, as well as to remain critical about excavation best practices. Furthermore, if future researchers had access to the system, they would be able to re-excavate the site digitally and see why and how decisions were made by the original excavators for use in future projects or site conservation. In essence, while the physical material may be lost, it continues to exist digitally.

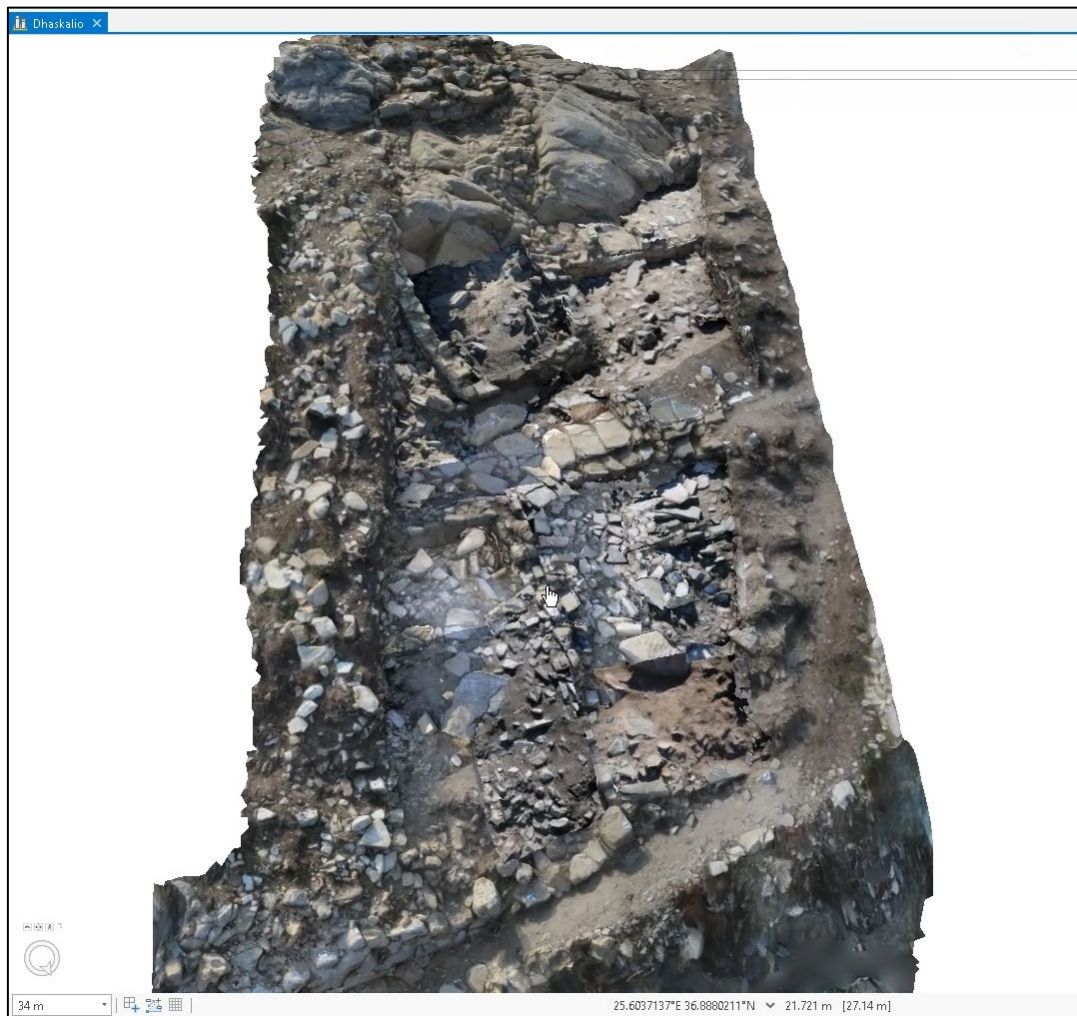


Figure 5-15 Showing the use of time to pinpoint which contexts were excavated on a specific day (09/09/2018)

5.2 STATISTICAL ANALYSIS AND CASE-STUDY

The aim of this section is to show the usefulness of this system as a statistical analytic tool, as well as its function as an integrated three-dimensional database. I will be utilising the ‘Density-based Clustering’ tool from the Spatial Statistics toolbox in ArcGIS Pro with the aim to recognise patterns of artefact clusters within

the SF data. Cluster analysis in various forms has been a statistical tool used by archaeologists for many years to identify groups in a set of data based on variables. It has typically been used to group artefacts based on chemical composition, typological similarities within an assemblage, and on the basis of the spatial location of artefacts (Hodson, 1970; Baxter, 2008; Ducke, 2015). It is the use of spatial classification that this case-study will utilize. In the section below, I will recount the steps taken to create the analysis, with concluding remarks on the potential interpretations of the analysis for understanding various site formation and taphonomic processes across the site and for recognising the activities of space within a trench.

5.2.1 The Density-Based Clustering Tool

The ‘Density-based Clustering’ tool is a part of the ‘Spatial Statistics’ toolbox in ArcGIS Pro. It works by detecting areas where points are concentrated and where they are separated by sparse or empty space. The tool uses machine learning clustering algorithms which automatically detect patterns based purely on spatial location and distances to neighbouring points and in this case is utilised in 3D (<https://pro.arcgis.com/en/pro-app/tool-reference/>, accessed 12 September 2020). The tool offers three clustering methods, ‘Defined distance’ (DBSCAN), ‘Self-adjusting’ (HDBSCAN), and ‘Multi-scale’ (OPTICS). The first uses a defined distance to separate out the clusters from noise, the second uses a range of distances to separate clusters, and the third uses the distances between neighbouring features to create a reachability plot which is used to separate clusters with varying densities (<https://pro.arcgis.com/en/pro-app/tool-reference/>, accessed 12 September 2020). The tool produces an output feature class which is automatically added to the map.



Figure 5.13 Example of how the Density Cluster Analysis tool works. From Esri <https://pro.arcgis.com/en/pro-app/tool-reference/spatial-statistics/densitybasedclustering.htm>, accessed 24 October 2020.

5.2.2 Clusters in Special Find Artefacts

The ‘Density-based Clustering’ tool is an ideal statistical analysis to explore the SF artefact data at Dhaskalio. As the SF data is comprised of points, running the analysis is a simple process. As this project was only interested in trenches B and H, first a new ‘Definition Query’ was added so that only artefacts from these trenches were visible. Next, the geoprocessing tool ‘Density-based Clustering’ was run and added in specific rules. For the example below, clusters must have a minimum of four artefacts within a 15 cm³ area, using the ‘Defined distance’ (DBSCAN) method, though the exact perimeters are up to the discretion of the user. This process was used to determine clusters of artefacts within the trenches for all artefact classes and initially taking into account all stratigraphic layers. The outputs can be seen in fig. 5.14 where the various clusters are colour coded to distinguish themselves from each other, while all non-clustered artefacts, or noise, are represented by small grey points.

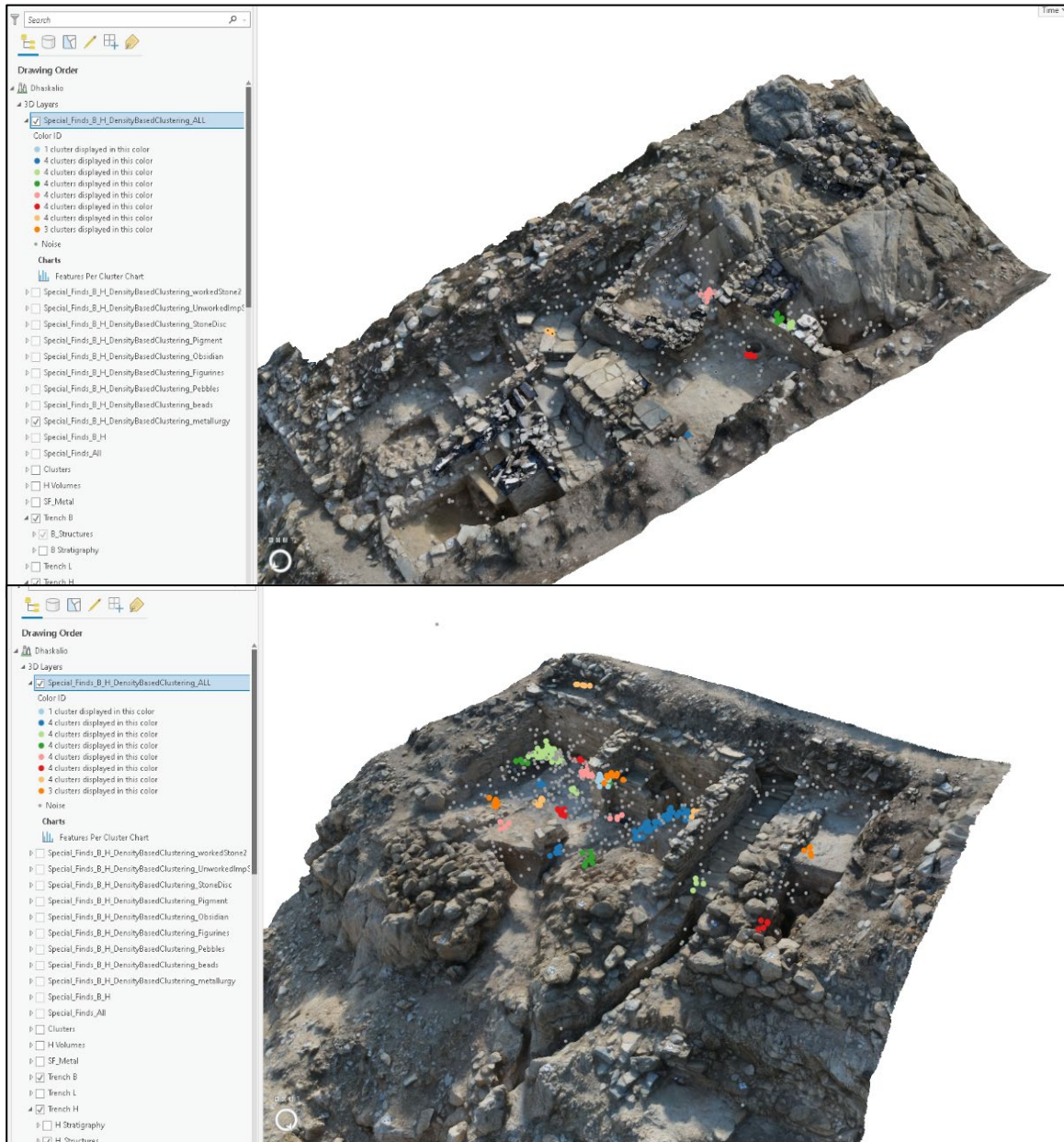


Figure 5.14 Clusters using all artefact types. Trench B (top) and H (bottom)

There is a clear difference in the nature of clusters between trenches B and H. While H has many identifiable clusters spread throughout the trench at lower levels associated with occupation events, the artefact clusters in B are located in more protected areas such as against walls. It could therefore be proposed that the taphonomic events differed between the two, with B's surfaces remaining less intact. This hypothesis would be better tested by looking at clusters found across all trenches of the site to determine if there is consistency in this pattern, such as the observation of a higher quantity of artefact clusters found in more protected trenches at stratigraphic levels of occupation, compared to trenches which faced damage from wind erosion or other natural forces that would affect the preservation level of their surfaces.

To take this analysis a step further, the stratigraphic layers in which the clusters were found can be turned on and viewed in section (fig. 5.15). In the case of a cluster in the south-east of trench B, artefacts were found in contexts 63 and 78. By looking at these artefacts in context and viewing the pop-up data for each artefact and stratigraphic layer, one could postulate that the nature of the cluster is



Figure 5.15 A cluster of artefacts with related stratigraphic layers visible, viewed in section using 'Exploratory Analysis' tool.

likely random. Contexts 63 and 78 are described as sediment build up below the tumble layers and a mixed deposit of roof and wall collapse, respectively. See supplementary material Video 6 for a clear example of how this process works.

To further test cluster analyses as a tool to clarify artefact distribution patterns and determine the use of space within a trench, another cluster from trench B will be examined. This cluster is distributed between contexts 43 and 46 and is located in a niche between the natural bedrock and wall 52 in the south-western area of the trench (fig. 5.14). The artefact cluster is made up several of Kouphonisi limestone pebbles and stone discs. It is possible that this area was used for storing artefacts of this nature. The deposit appears to be well preserved as the niche protected it from the strong northerly winds that affect the northern side of the island.



Figure 5-16 Cluster of artefacts found in niche between wall 52 and bedrock in trench B.

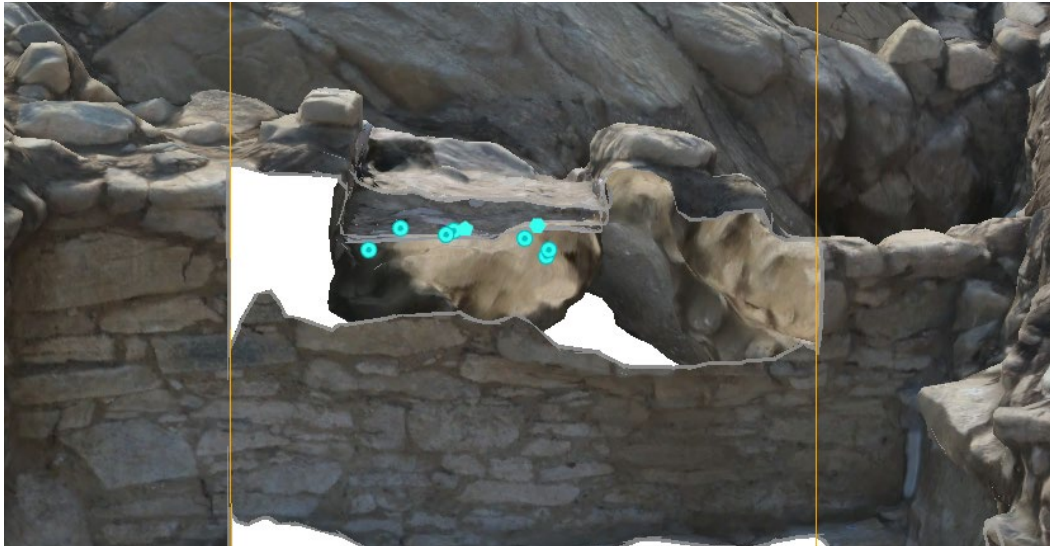


Figure 5-17 Using the 'Exploratory Analysis' tool to view the clustered artefacts in section. Note you can see the depth of the niche they sit in.

5.2.3 Single Strata Analysis

Importantly, Ducke (2015) notes that the detection of spatial clusters in archaeological settings can be difficult in 3D as it does not take into account that artefacts come from different stratigraphic layers. The proposed system is able to resolve this issue by the use of Definition Queries. A query can be added to the SF points where only artefacts from a specific layer will be applied (or a list of several layers if desired). While the initial test above using all finds across all trenches is useful to begin thinking about taphonomic processes and to determine general trends between the trenches, the latter method can be utilised to determine patterns within certain trench areas or within particular stratigraphic layers. For example, as

seen in figures 5.18 and 5.19 below. While it would be desirable to run each cluster analysis in a single operation, to maintain the best-practice of density based

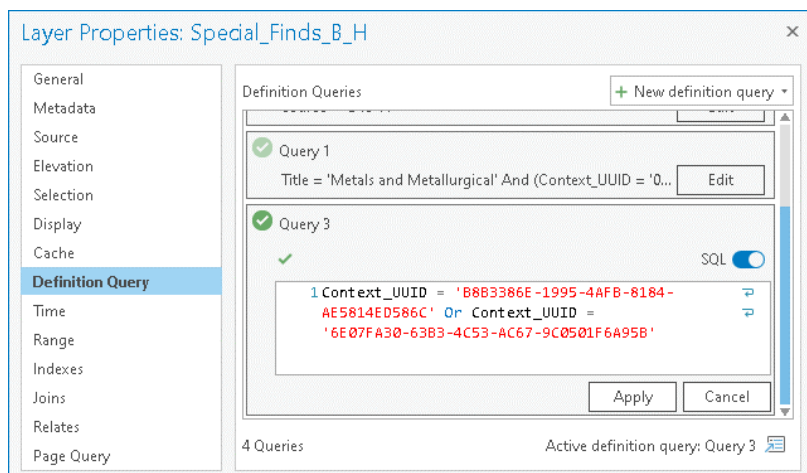


Figure 5-18 Example of Definition Query added to the SF layer to show only artefacts from two layers. These layers represent the surface 74 and its makeup 73, and as these strata are linked can be analysed together

clustering as noted by Ducke (2015), one must run each layer separately, so it will not consider artefacts belonging to different layers and thus different sequences. As this involves running individual definition queries through the proposed system, it is only possible to do this one stratigraphic layer at a time (or two at a time in the case where layers are irrefutably linked such as a surface and its makeup).

The results of this analysis in the given example show a cluster of six artefacts in Room 2 of trench H. Four of these artefacts are from the Metals and Metallurgy type, while the other two are lithics, one an Unworked Imported Stone and the other a Stone Disc. It can easily be determined which artefacts these are by creating a join as detailed in fig. 5.19 which will show the artefact information in the Attribute Table of the cluster analysis (fig. 5.20).

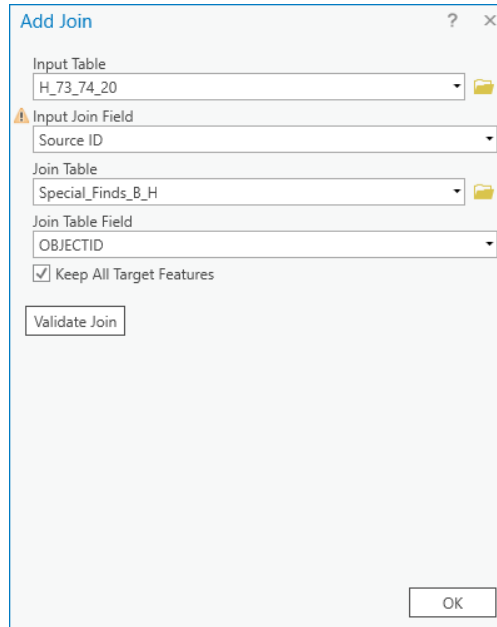


Figure 5-19 Add Join between the cluster analysis and the SF table

D	Color ID	OBJECTID	IdentifierUUID	Source	Type	Identifier	Title	Class
1	-1	4239	9F5F2770-52DD-4CAE-...	D19-H	Artifact	16158	Metals and Metallurgi...	<Null>
1	1	4240	FA24106A-BC77-47D6-...	D19-H	Artifact	16159	Metals and Metallurgi...	<Null>
1	1	4256	542D95F2-BA7E-46E8-...	D19-H	Artifact	16175	Metals and Metallurgi...	<Null>
1	-1	4260	25F6B674-BF49-4925-8...	D19-H	Artifact	16179	Pigment	<Null>
1	-1	4674	C2C969FA-52F3-44B7-...	D19-H	Artifact	4878	Stone Disc	<Null>
1	-1	4819	6362EB33-7933-4146-B...	D19-H	Artifact	5029	Stone Disc	<Null>
1	-1	4820	990F06EC-6B67-4109-8...	D19-H	Artifact	5030	Worked Stone	Lower quern/pivot s
1	1	4827	B883B476-C353-43E5-...	D19-H	Artifact	5037	Unworked Imported St...	<Null>
1	1	4832	56965A23-16B4-4C46-...	D19-H	Artifact	5042	Stone Disc	<Null>
1	1	4847	0F651A18-36CE-48A7-...	D19-H	Artifact	6802	Metals and Metallurgi...	Artifact
1	1	4854	61DBEF86-B796-42EA-...	D19-H	Artifact	16000	Metals and Metallurgi...	Spill

Figure 5-20 Screenshot showing the Attribute Table of the cluster analysis after the join has been made. This allows the user to look at the specific artefacts in the cluster with ease. Relationship in the cluster can read under 'Colour ID' where -1 represents noise.



Figure 5-21 Results of the cluster analysis of stratigraphic layers 73 and surface 74. Blue dots designate the cluster and grey show the 'noise'. Top image shows the results floating in the end of excavation model while bottom image shows artefacts in context with layers 73 and 74 turned on with 50% transparency

5.2.4 Metallurgical Finds

The presence of a hearth in trench H prompted a focus on metallurgical artefacts recorded. This was further driven by a comparison of artefact counts between the trenches, which showed that a much larger number of metallurgical artefacts were recorded in H (fig. 5.22). A density clustering analysis was run using all artefacts with a metallurgical nature. This included the categories ‘Metals and Metallurgy’, ‘Metallurgical Ceramic’ and ‘Hearth’. To do so, a ‘where’ clause was added and altered in the SF Definition Query, corresponding to each artefact class (fig. 5.23). Using the Density-based Clustering tool, the parameters were altered slightly. An increased space of 20 cm³ to account for the fewer artefacts tested was implemented. The result of this can be seen below in fig. 5.24.

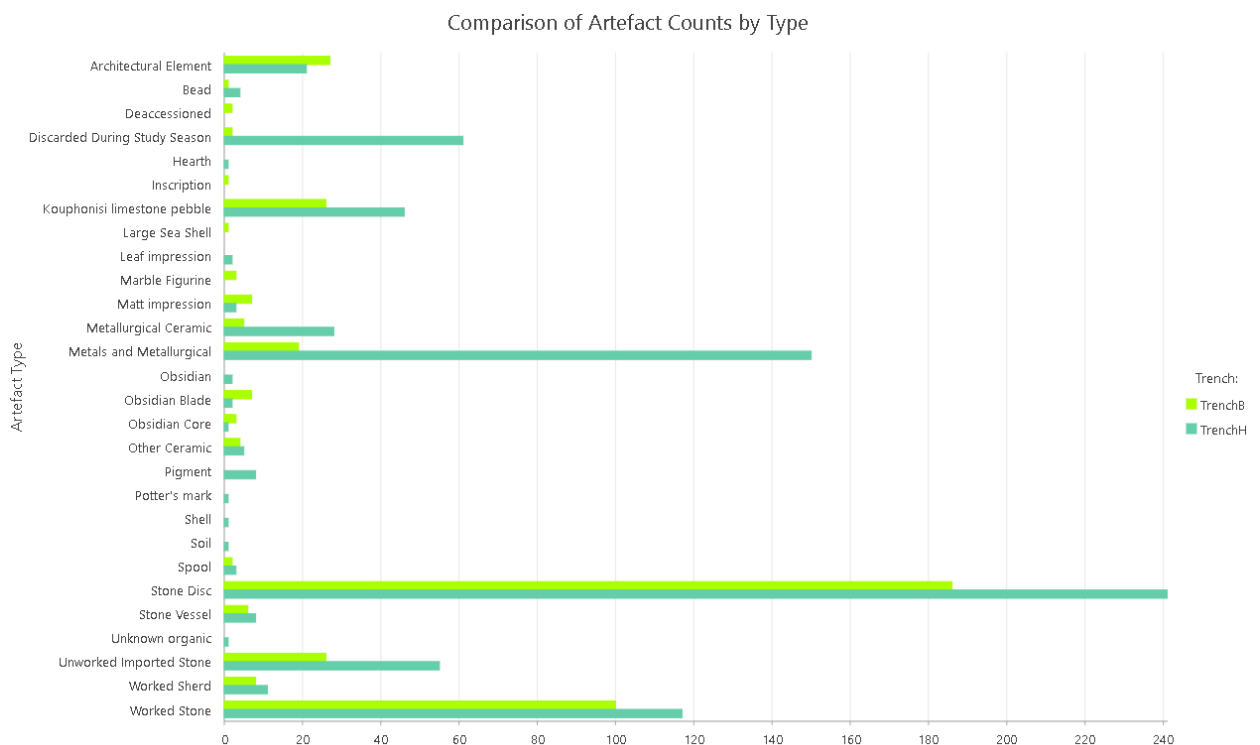


Figure 5-22 Counts of artefacts by type in trenches B and H, made in ArcGIS Pro

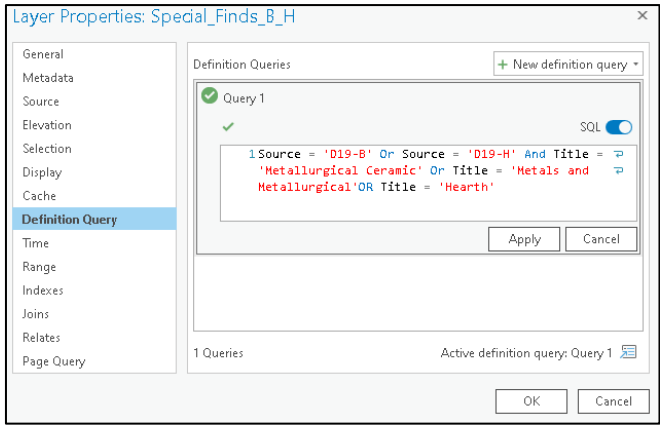


Figure 5-23 Definition Query used on SF data to test only metallurgical artefacts

In order to narrow down the data further, the automated cluster symbology was edited to use the material class as a variable (copper: triangles, gold: star, ceramic: diamond, scorched earth: circle). A join was then made between the analysis

layer and the fill/deposit table using the Identifier UUIDs, and from here we can easily view the artefact data in its entirety. Using a Definition Query, I then selected only the artefact clusters belonging to each relevant context. This is summarised in fig. 5.21 which shows the data in its table form in ArcGIS Pro.

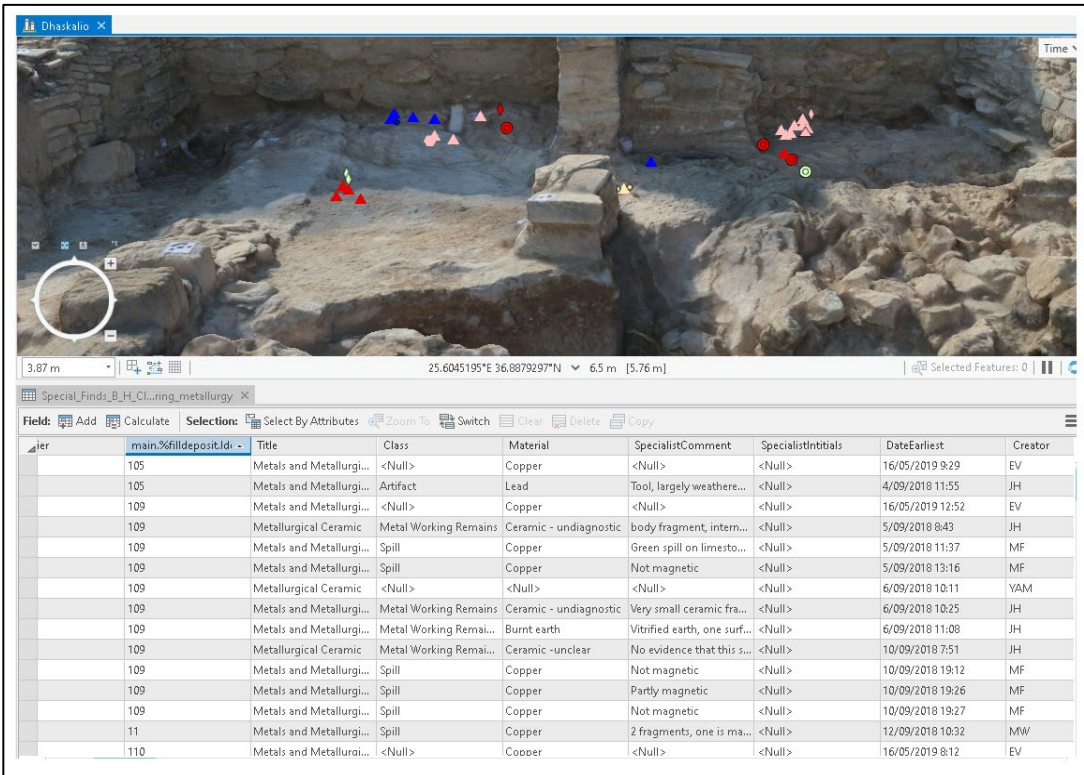


Figure 5-24 Density based cluster analysis of metallurgical artefacts from trench H with shape symbology characterised by material type

To take one example from the several clusters shown, the artefacts from context 98 likely relate to a metalworking area, with several copper artefacts, vitrified charcoal and burnt clay remains, as well as material related to the hearth (fig. 5.25). The artefacts themselves are clustered around the hearth feature, which has been dug into the bedrock. Furthermore, the metal remains all appear to be copper which suggests that the hearth was used to smelt copper. Interestingly, context 98 seems to be a significantly earlier phase than 73 and 74 highlighted by the previous example. They appear within the same area of Room 2, which suggests a continuation of metallurgical production over time.

main.%filldeposit.Idi -	Title	Class	Material	SpecialistComment
98	Metals and Metallurgi...	<Null>	Copper	<Null>
98	Metals and Metallurgi...	Artifact	Copper	Flat fragment, thinning at one end, knife fragment?
98	Metallurgical Ceramic	<Null>	<Null>	<Null>
98	Metals and Metallurgi...	<Null>	Copper	<Null>
98	Metals and Metallurgi...	<Null>	Copper	<Null>
98	Metals and Metallurgi...	Metal Working Remains?	Mineralised charcoal?	PXRF gave high Cu and Pb readings, material look...
98	Metals and Metallurgi...	Metal Working Remains	Burnt clay	Shapeless fragment, blackened, partly vitrified, no...
98	Metals and Metallurgi...	Metal Working Remains	Patch in the field?	Looks similar to 4915 and 4917, but much less mat...
98	Metals and Metallurgi...	Spill	Copper	Not magnetic
98	Metals and Metallurgi...	Metal Working Remains	Soil with charcoal	Hole in soil with grey/ black deposit, probably for...

Figure 5-25 Screenshot of attribute table summarising metallurgical artefacts from H, context 98

The analysis has shown some interesting points regarding distribution patterns within trench H as well as clarifying the used of space in rooms 1 and 2 as areas of metalworking with an emphasis on copper. Exploration of the data shows that the clusters are localised between a small number of contexts. While in-depth and extensive analysis of the site is beyond the scope of this thesis, it can be said with certainty that this system has the potential to be a versatile analytical tool.

5.2.5 Clarifying Distribution Patterns and Trench Taphonomy

By looking at visible patterns within the SF artefact clusters some conclusions can be drawn about the taphonomic processes at play in the site's sediment formation. In trench B, there are fewer artefact clusters, and none appear within contexts associated with surface event levels. The clusters that are present are located in well-protected areas, such as along walls, in corners of rooms, or within niches or cuts. Meanwhile in trench H SF clusters can be found distributed in lower surface event contexts and spread across the area of the trench, especially in rooms 1 and 2. Together this analysis establishes a difference in the preservation

levels within the two trenches and implies that different taphonomic events occurred in the burial processes of the site.

Furthermore, the above analysis has shown the use of this project for clarifying patterns of artefact distribution within the SF data. In trench B this was used to examine two SF clusters in the south-eastern and south-western areas of the trench. By examining the artefacts within the contexts they originated in, it was possible to draw several conclusions. Firstly, the cluster in the south-eastern area appears to have been a random group related to the layers of tumble, making it irrelevant for interpreting the division of space within the trench. The cluster of artefacts in the south-western area tells us more about the use of space. This cluster was composed of only two artefact types, stone discs and Kouphonisi limestone pebbles. The deposits they were found in were well preserved as they were protected by their location between the bedrock and wall 52. The niche this cluster was found in may have acted as a storage space with the purpose for storing these artefact types together.

The second example in this case study exemplified the ability to analyse specific layers within the site. Using layers 73 and 74 as an example of how the system is able to take into account this important factor, albeit in a less rapid manner. The results of this analysis showed that there was a cluster of primarily metallurgical material in the western area of the layers, perhaps signifying the processing of metals in the room.

A count of artefacts by their type showed a substantial quantity of 'Metal and Metallurgy' SFs in trench H, as indicated by the prior example. By running another density cluster analysis on only the metallurgical related artefacts, it was possible to discern the use of space in the western area of room 2 as an area where copper smelting was likely. More generally, it showed a wide spread of artefacts relating to the production of metals such as burnt clay, slag, and vitrified charcoal. Moreover, the second and third examples exemplified a pattern of activity within Room 2 as a metallurgical working space which was used through different periods of occupation at the site.

5.3 CHAPTER CONCLUSION

In all, this chapter has established that the workflow creates a fully integrated ‘living’ database of the site where both visual and statistical analyses can easily be applied to the excavation data of a site, using two trenches as an example. The methods posed here in conjunction with the example from the case study show that this approach can facilitate insightful conclusions about the site’s formation processes, and the relationships between artefacts and the use of space within the trenches. Furthermore, this approach simplifies the research component, where all site data is available within the GIS, minimising the need for outside software. This chapter has exemplified the many aspects of data exploration and analysis the proposed system provides, by integrating three-dimensional photogrammetric models of trenches B and H at Dhaskalio as tools in the analyses themselves.

6 DISCUSSION

This chapter discusses the interpretations and implications of the results presented in chapter 5. The first section will briefly summarise an overview of the presented workflow. Next, a review of the nature of the data and any limitations and issues present, including data sustainability will be made. The workflow will then be compared with those discussed in chapter 1's literature review to establish itself within the current research. Finally, the workflow and its results are discussed in terms of their interoperability and the diversity of data types where I will comment on the potential of this approach for intra-site analysis and data management.

6.1 WORKFLOW OVERVIEW

The workflow used to create this 'living', fully integrated 3D database is presented in detail in chapter 4, and here will briefly be summarised. The workflow presented in this research establishes a method for creating a holistic approach to two- and three-dimensional data storage and analysis. It does so by integrating the site's SQL database with ArcGIS Pro. The excavation's archaeological database was set up using PostgreSQL on a hosted server which was connected to ArcGIS Pro. This means that the data can be edited in either the 'back end' or the 'front end' and the results will be displayed between the two immediately. This allows the database to be 'living' in the sense that it can constantly grow as modifications are made and data is added over time. Once any data cleaning was done within the database tables, all tables and geo files were added to the GIS. Next, the 3D models of the site's architecture, contexts, and trenches were added, and the relevant data joined to the corresponding database tables. Following this, attachments, such as field photographs, were added to the SF artefacts, the 3D contexts, and the architectural models. Attachments were also added to a table containing references to relevant literature and publications and to field notes and matrices. Next, the pop-ups were configured to display a user-friendly array of data and the attached photographs. Finally, symbology of the SF points were modified to reflect real world representations of the artefact classes

for easy identification, and the component of time was organised for the SF and context data based on timestamps in the database.

6.2 NATURE OF THE DATA

It is important to address the nature of data used within this research. The data used in this project was certainly not without its flaws, nor the workflow itself. The scale of this workflow may not suit all projects given the financial and time investments required. These issues will be examined and discussed in more detail below.

Some of the tabular data required cleaning to make it possible to run queries. This was a result of the iDig recording system where each user titled artefact categories slightly differently. While this was time consuming, it was simple to fix with basic ‘find and replace’ tools in the SQL database (though could also have easily been done within the GIS). However, this was something that could easily be avoided with more rigid recording strategies. A stricter explanation of what was acceptable by the field supervisors, or a selection of categories from a drop-down list, for example, would have worked well to mitigate this problem.

Another issue that must be addressed is the differences in colour values of the textured photogrammetric models. Differences occurred due to weather conditions and the time of day that photographs were taken in the field. As noted prior, some have addressed this issue by taking photographs at approximately the same time each day (see Waagen 2019 for using UAV end of day photographs), this would not have been a suitable approach for the Dhaskalio excavation and documentation methods which required a fast turn around and a 3D model of each stratigraphic layer. Excavations are often on a strict time limit, making it impossible to stop excavation in an area so frequently, waiting for the ideal lighting conditions. Furthermore, the 3D models act as a representation of how the trenches and contexts appeared to the excavators at its time of removal, which in itself is valuable for understanding an excavator’s interpretations. The consistency in which excavators took photogrammetry for every context meant that the only missing 3D data came from the surface make-up contexts, which as discussed in chapter 4, was worked around by making a copy of the surface’s model and making a note. Further, the fast turnaround of processing models in the lab on a daily basis meant that the lab

processor (being myself) had a strong understanding of which contexts to expect from trenches, and could keep track of the data quality coming out of the field.

Time management and man-hours are a clear concern in this workflow. Even with the processing time in the field lab taken out of the equation, joining each three-dimensional model to its context data and attaching the relevant photographs and files is extremely time consuming despite the incorporation of several time-saving python scripts. A solution for this is that the system should ideally be set up and used from the beginning of an archaeological project. The presented workflow should become a part of the wider excavation documentation procedure. A design for its implementation in the excavation process for projects utilising photogrammetric recording is suggested in the figure below. Not only would this spread the work out into manageable allotments, but it would also encourage reflexivity in excavation and documentation practises during the excavation itself.

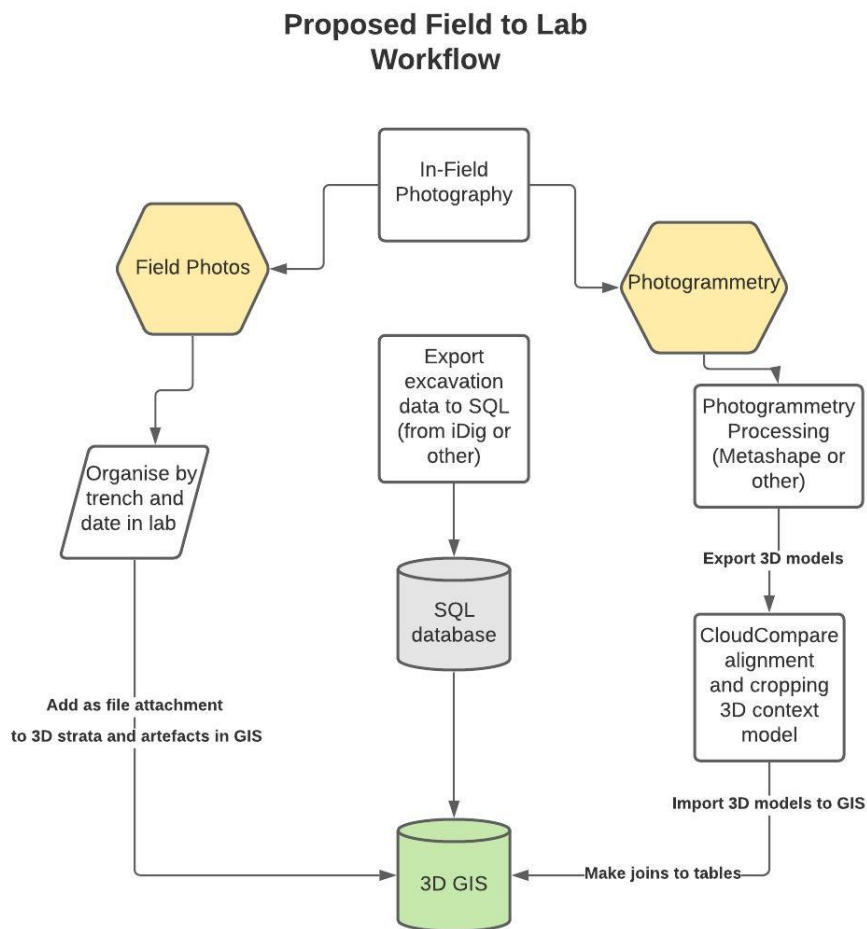


Figure 6-1 Suggested field to lab workflow for incorporating 3D GIS and photogrammetric models into documentation procedure

The system presents itself as flexible and adaptable to projects of different sizes and needs. The Dhaskalio dataset contains a huge amount of data and it is not expected that every project will have taken a photogrammetric recording of every excavated context, for example. One would easily be able to use the basic workflow to incorporate the 3D data better within the site recording and analysis processes. This workflow allows a project to incorporate both 2D and 3D excavation data in a single place for easier distribution, access, and assessment.

The final concern for this workflow is the technological and computing power requirements. The proposed workflow was created using a Dell gaming laptop with 32 GB of RAM, an Intel Core i7 processor, and a dedicated NVIDIA GeForce graphics card. While home computers have become more powerful and are available at a lower cost than previously, it should be stressed that this project would not have been possible without a dedicated graphics card and high amount of RAM due to the strain of rendering many 3D files in a single scene. As more data is added and other trenches incorporated into the system, the more processing power will be required.

6.3 DATA ACCESSIBILITY AND SUSTAINABILITY

Another concern of this project relates to data accessibility, storage capacities, and sustainability. Hundreds of 3D photogrammetric models are required for this project to function, as well as thousands of photographs. This hasn't become unmanageable for the Keros Project. In total, three years of excavations have produced approximately 3.8 TB of work, which includes the 3D models, orthophotos, DEMs, and photogrammetry photograph sequences, and artefact photographs all fit onto a 4 TB portable HDD, but is certainly a potential issue that should be acknowledged. The ArcGIS Pro project file is currently 35 GB, and with only two of the site's eight trenches currently imported. I would estimate that to incorporate all eight trenches, the file would find itself at over 100 GB. This may also impact data sharing. The ArcGIS Pro project can be exported to a .zip file and shared with anyone with access to the software, though the large file size may make this less easily accessible to some. Access to ArcGIS Pro itself is a potential issue in data accessibility, as it requires a proprietary license of the software from Esri. This cost can be alleviated somewhat by the use of a student or institution

license often available within universities, while a low-cost personal license is otherwise available. As stated in prior chapters, it is hoped that the workflow posed in this thesis will be simple to enact in open source platforms of GIS when such software offers better integration and support for three-dimensional layers.

Sustainability of the files themselves has been considered in the file types used and especially in the type of database chosen. The photogrammetry 3D files were exported as .obj types as it is a neutral format that is commonly supported in many popular 3D software, making it interoperable between them (Pilzecker, 2020). The interoperability of the database was another important factor in this project. Databases using FileMaker and MS Access are no longer compatible with current ArcGIS products, and are becoming obsolete as client-server and other database management systems become more popular. Storing data in the SQL format should ideally guarantee support and compatibility in years to come as it has been a standard of the ISO (International Organization of Standardization) since 1987 and continues to be one of the most popular database languages (International Organization of Standardization, 2016).

6.4 OTHER METHODOLOGIES

3D GIS databases created by several other projects were outlined in chapter 1. This section will use these examples to compare this proposed system against those already established. Of the other methodologies explored, several points stand out. Firstly, each one has a strong incorporation of visual analysis with the exploration of three-dimensional representations of archaeological data. Secondly, there are two distinct types of 3D GIS used in these projects – either with the incorporation of Esri’s ArcScene, or by using a custom web-based GIS. Finally, each project uses exceedingly different sizes and types of datasets taken from distinctly different sites.

Web-based custom GIS with 3D support is used in the MayaCityBuilder and at Alken Enge, in Denmark using the Archaeo3D-Viewer each utilising databases based on SQL. Both Richards-Rissetto (2017) and Jensen (2018b) note the data sharing benefits of a web-based system, especially for educational and hypothesis sharing ventures, but they also acknowledge the difficulties attributed to rendering large three-dimensional files in an online environment. Both projects also employ

the use of segmented annotation of the 3D models, which allows one to split the model up into various pieces and associate relevant information based on the selection. Certainly, the ability to customise a 3D GIS for the specific needs of a project is an attractive feature, however these platforms require in-depth IT skills to set up and produce. Whether or not the needs of different projects are so distinct from one another to require or justify this effort is questionable if other options are available that offer more user-friendly interfaces and well-documented support systems. Nevertheless, a unique capability of the MayaCityBuilder is its incorporation of procedural modelling, which allows the user to test hypotheses based on known architectural parameters. This addition is valuable for model building on a wider regional scale.

Many of the projects make use of the ArcScene extension of ArcGIS, a common proprietary GIS platform. Due to the limitations of ArcScene as a database management system, the Çatalhöyük (Forte et al., 2015; Lercari et al., 2018) and Pompeii Insula V (Dell'Unto et al., 2015) projects used supplementary systems to allow users to access all the site's information. In Çatalhöyük this was done using Dig@IT, a VR software developed by Duke University for the project, while the Pompeii Insula V project used hyperlinks to link the available information from the project's website. Meanwhile the Kampinge project (Dell'Unto et al., 2017) in Sweden utilised both ArcScene and the accompanying Collector app in the field, which created an internal ArcGIS geodatabase which allowed for a flow of information in a single environment. The final project examined is the Chlorakas-*Palloures* volumetric model project which used Total Station data and section drawings to create 3D volumetric models of the site's stratigraphic record (Gavryushkina, 2018). Unfortunately, each of these projects had to make concessions in interoperability due to the limitations of the ArcScene platform, which does not support some simple tasks such as showing labels on objects and layers.

While some of these projects allege their database functionality (and support the claim with valid definitions), they often do not incorporate the many facets of site information nor allow for easy access to additional files. The Chlorakas-*Palloures* project for example runs on excel spreadsheets amended from an MS Access database which is a filetype no longer supported in many GISs and means

that any edits made within the GIS environment will not be reflected in the site's database. Similarly, the Pompeii Insula V project forces the user to view the information in a web browser rather than having access to the information in a single environment. Likewise, this system would not allow for edits to the data to be made within the GIS. The Çatalhöyük project also requires additional software to access all of the information, made more complicated by the software's production being custom-made for Çatalhöyük. Additionally, with the exception of the web-based platforms and the Kamping and MayaCityBuilder projects, the above methodologies do not enable a sustainable method of accessing a site's data which can be added to and grown over time. Curiously, despite its release in 2015 and accessibility with an ArcGIS institutional licence, none of the projects apparently investigated using ArcGIS Pro. The benefits of this software over ArcScene and ArcMap were discussed in more detail in chapter 2 and are worth noting. To this author's knowledge, there have been no projects publishing on using ArcGIS Pro to create a three-dimensional database for an archaeological project.

The scale in which these projects were undertaken is another interesting comparison to make. While this thesis used the data of two trenches from Dhaskalio, it would be possible to use the method for all eight trenches excavated between 2016-2018 on the site. The topography of Dhaskalio is extraordinarily steep and rugged with deep trenches and complex architecture. Each of the above projects were run at much smaller scales and in flatter, more forgiving terrain with less complex architectural remains, and were tested either in fewer, smaller trenches or a single room as at Çatalhöyük. While the Pompeii Insula V project contains a large amount of complex architecture, the conditions allowed for a single laser scan of the site to be made, while excavation strata and artefact data were not used. Likewise, it is difficult to compare the sheer scale of the MayaCityBuilder project which is largely based on procedural modelling rather than as a three-dimensional representation of an excavation.

The final point of comparison is the different types of analyses used in the projects' data. This has been simplified and broken down in table 6.1, below. All of the projects, including the Dhaskalio dataset, provide robust platforms for visual analysis and exploration of the imported meshes in 3D. Each of these also supports the use of querying and filtering the data based on specified parameters by joining

the database to the three-dimensional data. However, there is a clear shortcoming in several of these in the lack of quantitative or statistical analyses. The MayaCityBuilder notes that this is a facet of analysis currently being worked on within the project (Richards-Rissetto, 2017; Richards-Rissetto & von Schwerin, 2017). Only the Pompeii Insula V and Alken Enge projects have published the use of quantitative analysis of the three-dimensional data. The former by using detailed photogrammetric models of frescos to classify their level of preservation and lists their conservation needs (Dell'Unto et al., 2015; Dell'Unto, 2016), and the latter proposes the use of machine learning in posthole classification (Jensen 2018a, 147-159).

The failure to incorporate three-dimension data in a more meaningful way than for visual reconstructions of archaeological remains has been well noted (Roosevelt et al., 2015; Dell'Unto et al., 2017; Richards-Rissetto, 2017; Magnani et al., 2020). This point has been a primary motivator in this project and has led to the use of unsupervised machine learning statistical tests such as the 'Cluster-based Density' example used to determine patterns in the SF artefacts in trenches B and H which have been used to make hypotheses based on the taphonomic processes between the trenches as well as the uses of space in rooms.

A positive outcome of this method has been the creation of a dynamic system that negates the need for multiple programs and software to run. Furthermore, it does not discount the value of 2D data, but rather encourages the user to interact between all data types in a single environment. This has strong benefits over previously proposed systems where the 3D environment is run separately in ArcScene, for example. This workflow also negates the need for more complex coding and customisation of web-based systems which are certainly not a possibility for many projects.

Project/Site	GIS Type	Database Type	3D Data Acquisition	Visual Analysis	Querying	Quantitative /statistical Analysis	Other Analysis
Çatalhöyük, Turkey	ArcScene Dig@IT (custom)	SQL	Laser Scanning SfM Photogrammetry	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
MayaCityBuilder	Web-based Geobrowser (custom)	PostgreSQL/PostGIS	SfM Laser Scanning Procedural Modelling	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Procedural Modelling
Chlorakas-Palloures, Cyprus	ArcScene	MS Access/Excel	SfM Photogrammetry Total Station Extrapolation	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
Kampinge, Sweden	ArcScene	ArcGIS internal geodatabase	SfS Photogrammetry Total Station Extrapolation	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
Alken Enge, Denmark	Web-based (custom)	MYSQL	SfM Photogrammetry	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Pompeii Insula V	ArcScene	unknown	Laserscanning SfM Photogrammetry	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Keros Project - Dhaskalio	ArcGIS Pro	SQL	SfS Photogrammetry	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	

Table 6-1 Table summarising projects discussed and their methods

7 CONCLUDING REMARKS

Now that 3D technologies have become more commonplace, it is time to rethink and reassess the way that we as archaeologists handle our data. As digital field recording methods becoming more standard, a simple workflow to store, explore, and analyse the vast quantities of 2D and 3D data collected over the course of a project is exceedingly beneficial. While the complexity of archaeological excavation data poses a challenge for any information system, the research presented here has demonstrated that the integration of 3D data and 3D models for analysis is available within current technologies.

This thesis posed the question of whether it is possible to synthesise 3D data with excavation data to create a useful product. The system created through the proposed workflow was able to successfully incorporate 3D data into a GIS database and proposed ways of using 3D models as part of the interpretative process. The 3D data was made interactive by use of pop-ups that allowed the user to explore the trench's excavation. The joining of tabular, image, and 3D data within the same 3D GIS system created a simple way of managing excavation data in a single environment.

An essential aim of this thesis was to determine the contributions that photogrammetry and image-based 3D models can make to post-excavation analyses. The proposed workflow allows for the easy integration of 3D data as part of the intra-site analysis procedure. 3D models are retained within the excavation database as part of the GIS where they can be filtered, viewed, and assessed in association with other 2D and 3D datasets. The analytical potential of field-recorded 3D model was explored through a machine-learning tool for the cluster analysis of artefacts. This was used in tandem with 3D models taken of the stratigraphic layers to assess the taphonomic events of the site. Further analysis was exemplified by examining clusters of the Special Find objects where distribution patterns surrounding trench H's metallurgical artefacts were looked at in more detail. This analysis revealed a consistent use of Room 2 as a place of metallurgical processing over different phases of occupation. These results show the potential of 3D models as more than a simple means of visualisation and a three-dimensional

‘pretty picture’, rather exemplifying their potential to aid researchers in the post-excavation process of intra-site analysis.

This thesis stressed the importance for both interoperability of the workflow and the significance of FOSS frameworks for future research. While the workflow used to create the system for Dhaskalio relied on proprietary software, a more general workflow was also discussed in the event that a robust open-source 3D GIS software is made available in the future. It is hoped that the incorporation of more general steps will shift the focus from the user interface itself to the more important aspects of the proposed workflow model. This general approach was based on tools that open-source traditional GIS platforms such as QGIS already contain and therefore are likely to appear in future versions. Meanwhile the decision to use an SQL database hosted on a server made the system capable of ‘living’, in the sense that edits made in the GIS would be visible immediately in the database and vice versa. This is an important aspect for sharing the data. It allows the GIS to work as a ‘front end’ capable of accessing, viewing, and analysing the data while the SQL database acts as the ‘back end’, where it can be opened and edited by anyone with access. The problems created by the accumulation of vast quantities of spatial data well known to archaeologists could be mitigated by the implementation of this workflow, creating a common database containing all files relevant to an excavation in a single system. Overall while the entire workflow from field to 3D GIS was laborious, a more structured integration of the entire system within an excavation would certainly help mitigate this issue.

Future directions in 3D GIS and the integration of 3D models in archaeological databases are plentiful. Projects using three-dimensional stratigraphic models that were extruded based on polygon data and Total Station measurements or similar methods as opposed to photogrammetry, may benefit from the incorporation of colours of each stratum based on the excavator’s description. Ideally, this would be done using the Munsell chart where it can be assumed the observations were consistent site-wide. Another possibility would be to add a texture to these models based on photographs taken of the context. Of course, neither of these would be true representations of the stratigraphy’s colour values but may help users visualise the trench more accurately. Another direction to be explored is the incorporation of segmentation of 3D models to allow for different annotations to be attached to

different regions of the same model. This would be especially useful for annotating the architectural models and has been used in procedural modelling. The incorporation of legacy data into the GIS system would be of further benefit. Information from the previous excavation phase, even with less data stored in the third dimension would aid in the overall site's interpretation. Where Z levels are available, for example in the case of the polygon or polyline and levels of a stratigraphic unit, it would be possible to reconstruct the strata based on methods implored by Gavryushkina (2018) and Landeschi et al. (2019). Having all of this data within a single system would certainly aid in the site interpretation, and also bring together the overall project excavation more holistically. Finally, in the realms of artefact cluster analysis and intra-site analysis, it would be possible to use the cluster tool on specific layers that corresponded to the same occupation phases across the site. For example, in the case of Dhaskalio a definition query could be run to only use artefacts and layers site-wide that correspond to Phase II. This would allow for a site-wide inspection of clusters which may aid in the determination of how space was used across the island in a specific time period.

The workflow proposed in this thesis frames the basis for further developments of dynamic data management approaches and the integration of complex spatial and three-dimensional data with images and text data. This system represents a departure from more static uses of three-dimensional data and conventional methods of visual analysis by creating a flexible and fully integrated system that encourages reflexivity while fostering the use of three-dimensional spatial data in archaeological practices.

ABSTRACT

The analytical function of 3D data beyond visualisation and aesthetics has been a well-discussed issue in archaeological literature. Several recent projects have proposed case studies and workflows that implement three-dimensional data in 3D GIS software, yet few have truly utilised 3D modelling as a valued part of the analytical process. This begs the question, is there an added value of 3D approaches over traditional GIS, and what kinds of analytical possibilities does 3D documentation provide? This project aims to address these questions by integrating all available site datasets in a single, ‘living’ 3D GIS database which can be accessed and edited either in the ‘back end’ SQL database or the ‘front end’ 3D GIS. Furthermore, this project integrates 3D models created by structure-from-motion photogrammetry and establishes a number of useful analytical tools for working with three-dimensional spatial data, such as using artefact clusters to determine the function of space, and to comment on the taphonomic processes of the site.

This project introduces the workflow for a fully integrated, interoperable database using 3D GIS, whereby three-dimensional data can be stored, viewed, and analysed alongside traditional GIS components and relevant site data such as (but by no means limited to) photographs, published related literature, and field notes. The project utilises the data from trenches B and H at Dhaskalio, Greece, excavated between 2016 and 2018. This site presented an ideal case study for the incorporation of 3D models as the project aimed to use an entirely digital recording system with photogrammetric models taken of every stratigraphic layer excavated and each architectural feature on site. This approach presents an advantageous use of 3D data in the intra-site interpretation processes.

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LIST OF FIGURES

Figure 1-1 Examples of DEM (left) and orthomosaic (right) of Dhaskalio (by author).....	8
Figure 1-2 Diagram demonstrating the process of reconstructing an object using structure from motion (from Moulon, Monasse, and Marlet 2012, fig. 2)	10
Figure 1-3 Demonstrating high-resolution photogrammetry and precise measurements. 3D reconstruction of a Mycenaean child burial at Khirra, Greece. Created using Agisoft Metashape (by author).	11
Figure 1-4 3D model of Caecilius Iucundus, insula V 1 at Pompeii in the ArcScene environment. (From Dell'Unto 2016, fig.5, 315)	14
Figure 1-5 Screenshot from the Archaeo online database. (From Jenson 2018a Fig.4.7, 132).....	17
Figure 1-6 Keros and the Little Cyclades. Dhaskalio indicated by star (from https://www.arch.cam.ac.uk/research/projects/current-projects/keros-project , accessed 10 December 2020).....	19
Figure 1-7 Plan of Dhaskalio showing excavation trenches; 2007-2008 and 2016-2018 seasons. Trench B (blue circle) and Trench H (yellow circle) (by author). .	21
Figure 2-1 2.5D (top) and 3D (bottom) models of Dhaskalio, illustrating differences in quality (by author).....	26
Figure 3-1 Dhaskalio and Kavos from the west. Contours at 0.5 m and 5. intervals. (From Renfrew et al. 2009, fig. 1, 29.)	31
Figure 3-2 View of Dhaskalio from the Special Deposit South on Kavos (from Renfrew et al. 2012, fig. 5, 151.)	32
Figure 3-3 Chronology the phases at Dhaskalio. (From Renfrew et al., 2012, table 6, 155.)	33
Figure 3-4 Trenches opened in 2016-2018 seasons labelled in red (from https://chronique.efa.gr/?kroute=report&id=6541#true-1).....	34
Figure 3-5 Collapsed staircase in Trench B, showing different elevation levels of rooms and areas (by author).....	35
Figure 3-6 Map of Trench B with features and areas labelled. Walls coloured pink. (by author)	36

Figure 3-7 Photo of Dhaskalio taken from UAV showing trench B (circled) in its position above the steep cliff face (by author).....	37
Figure 3-8 Trench H, view from the North (by author).....	38
Figure 3-9 Plan of Trench H showing different designated areas (by author)	38
Figure 3-10 Trench H from above, exemplifying the degradation of the eastern side and proximity to the water. (by author).....	39
Figure 4-1 Screenshot of iDig showing plan of Trench B with all layers turned on (left) and spatial matrix created by iDig (right).....	41
Figure 4-2 Flowchart of Dhaskalio's photogrammetric processing	42
Figure 4-3 Error Margin example per metre and pixel as seen in Agisoft Metashape for Trench H 2018 end of excavation model.....	43
Figure 4-4 A screenshot of DB Browser showing the 2016-2018 Dhaskalio database as an SQLite file schema.....	45
Figure 4-5 PostgreSQL database viewed in PG Admin.	46
Figure 4-6 Flowchart showing an overview of the workflow described below. More general steps for future software in red. Non-mandatory steps shows with dashed line.	50
Figure 4-7 Database Connection tool prompts the log in information to the server	51
Figure 4-8 Databases connected to the GIS showing the IP address and tables/data available to add to the map as well as the internal geodatabase produced by ArcGIS Pro.	51
Figure 4-9 Contents pane showing the division of stratigraphy between rooms/spaces in trench H as well as the structures in a single grouped layer	52
Figure 4-10 Trench H end of excavation 3D model imported into the GIS	53
Figure 4-11 Joins in ArcGIS Pro to add excavation and specialist data to the 3D models.....	54
Figure 4-12 Example of script supplied by ESRI and modified by author to add join between a 3D object and the data table	54
Figure 4-13 Table showing literature related to the excavation. This was imported via a CSV derived from a Zotero library.	55
Figure 4-14 Example of script supplied by ESRI and modified by author to enable and add attachments to layers.	55

Figure 4-15 Pop-up (left) and customised HTML code (right) and the ‘Configure Pop-ups’ pane (bottom).	56
Figure 4-16 Formatting the symbology of artefacts to represent their artefact type	57
Figure 4-17 Layer properties of a context, turning on 'time' component.....	58
Figure 4-18 Example of how the time slider works (from Esri, https://pro.arcgis.com/en/pro-app/help/mapping/time/visualize-temporal-data-using-the-time-slider.htm)	58
Figure 5-1 Flowchart showing the various inputs and outputs of the proposed system.	60
Figure 5-2 Edit made externally in database using PG Admin (top) immediately reflected in ArcGIS Pro environment (bottom)	62
Figure 5-3 Accessing file attachments stored in the GIS. A journal article is opened in the default PDF viewer by double-clicking the file in the GIS.....	63
Figure 5-4 Polyline and Polygon data can be viewed either in 3D (top) or planar 2D (bottom).....	64
Figure 5-5 Contents pane showing different 3D models of contexts from Trench H	65
Figure 5-6 Trench H, showing all Special Find points in the GIS.....	66
Figure 5-7 Trench B, Special Find pop-up with the SF clicked on circled in red .	66
Figure 5-8 Pop up showing details and photographs of structure 42, a drain (circled). Other nearby objects can be toggled at top of pop-up (circled on pup-up)	67
Figure 5-9 Using Exploratory Analysis tool to view a cross-section of the stratigraphic sequence in Room 3 of Trench H	68
Figure 5-10 Artefacts from Surface 116 showing locations within stratigraphy using the Exploratory Analysis tool.....	69
Figure 5-11 Definition Query used to filter layers to context 116, trench H.....	69
Figure 5-12 Colouring architecture by phasing. Dhaskalio island (top), Trench B (bottom left) and Trench H (bottom right).....	70
Figure 5-13 Using 'Measure Distance' tool to measure the length of wall 52 in trench B, compared with measurements taken in the field as seen in the pop-up .	71

Figure 5-14 Estimated volume of surface 116 in trench H using 'Estimated Bounding Volume' tool, with only SF artefacts from 116 visible.	72
Figure 5-15 Showing the use of time to pinpoint which contexts were excavated on a specific day (09/09/2018).....	73
Figure 5-16 Cluster of artefacts found in niche between wall 52 and bedrock in trench B.....	78
Figure 5-17 Using the 'Exploratory Analysis' tool to view the clustered artefacts in section. Note you can see the depth of the niche they sit in.	79
Figure 5-18 Example of Definition Query added to the SF layer to show only artefacts from two layers. These layers represent the surface 74 and its makeup 73, and as these strata are linked can be analysed together	79
Figure 5-19 Add Join between the cluster analysis and the SF table	80
Figure 5-20 Screenshot showing the Attribute Table of the cluster analysis after the join has been made. This allows the user to look at the specific artefacts in the cluster with ease. Relationship in the cluster can read under 'Colour ID' where -1 represents noise.....	80
Figure 5-21 Results of the cluster analysis of stratigraphic layers 73 and surface 74. Blue dots designate the cluster and grey show the 'noise'. Top image shows the results floating in the end of excavation model while bottom image shows artefacts in context with layers 73 and 74 turned on with 50% transparency	81
Figure 5-22 Counts of artefacts by type in trenches B and H, made in ArcGIS Pro	82
Figure 5-23 Definition Query used on SF data to test only metallurgical artefacts	83
Figure 5-24 Density based cluster analysis of metallurgical artefacts from trench H with shape symbology characterised by material type	83
Figure 5-25 Screenshot of attribute table summarising metallurgical artefacts from H, context 98.....	84
Figure 6-1 Suggested field to lab workflow for incorporating 3D GIS and photogrammetric models into documentation procedure	89

LIST OF TABLES

Table 4-1 Table summarising the differences between SQLite and PostgreSQL database types	46
Table 4-2 Table summarising data types used in this project.....	47
Table 4-3 Software used by in this project	48
Table 6-1 Table summarising projects discussed and their methods.....	95

SUPPLEMENTARY MATERIAL

File 1: Video_1_Matrixes_PDFs_Attachments

File 2: Video_2_TrenchB_SF_Popup

File 3: Video_3_TrenchH_Structure_Interaction

File 4: Video_4_Special_Find_Queries

File 5: Video_5_Trench_B_Time

File 6: Video_6_Cluster_Analysis_Segemntation

Accessible from:

<https://we.tl/t-8vY6nCzvBF>