Curtin HIVE (Hub for Immersive Visualisation and eResearch)
and the School of Earth and Planetary Sciences

Photogrammetric Analysis of 4th Century BC Kyrenia Shipwreck

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*“**Photogrammetric Analysis of 4th Century BC Kyrenia Shipwreck**”*
Curtin HIVE internship report (2020).

Abstract

Using modern technologies, new information can be obtained from past archaeological records. For instance, historical site diagrams from a shipwreck survey can be revisited and verified through a process known as photogrammetry. This project involves photogrammetric 3D reconstruction of legacy photos of the 4th century BC shipwreck Kyrenia.

In 1967 to 1969, the Kyrenia shipwreck was excavated off the north coast of Cyprus by a team of nautical archaeologists. Some key findings of the survey were antique cargoes comprising of amphorae and millstones. For these cargoes, site diagrams were originally drawn on-site, during excavation. At the same time, 2D photos of the site were captured. In this current age, these photos have the potential to verify the accuracy of the original site diagrams through photogrammetry.

This project focussed on three areas of the excavation: the 1967 amphora mound, the 1968 millstones, and the 1969 millstones. For each site, a digital 3D model was reconstructed using the legacy photos. Then, an orthomosaic map was derived, so that it can be overlaid with the original site plan. This overlay allows comparison and analysis between these two diagrams, verifying whether the old site plan was drawn accurately.

Comparison of the orthomosaic maps to the original site diagrams showed a satisfactory fit but also a fair amount of positioning error. Additionally, error analysis of the overlays resulted in RMSE values of 4.31cm, 7.43cm and 4.38cm for the 1967, 1968 and 1969 environments respectively, which are reasonable quantities, particularly when compared to the overall environments which span several square metres.

We have therefore found it is feasible to use photogrammetry to verify site diagrams and even create them, with potentially higher accuracy.

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1. Introduction

1.1. History

In 1967 to 1969, a 4th century BC Kyrenia shipwreck was excavated off the north coast of Cyprus (Green, et al., 1967; Katzev, 1970), at a depth of 33 metres (Höhle, 1971). The wreck is one of the most significant Classical Greek Period shipwrecks to have been discovered.

The vessel was completely excavated, and the surviving timbers were conserved and rebuilt in Kyrenia Castle, Cyprus. Some key findings of the survey were cargo that comprised of amphora and hopper-type millstones (Steffy, 1985). The amphora mound was discovered at the start of the survey in 1967 while the millstones were exposed when the site was being excavated during the middle of 1968. Site diagrams had been drawn and formulated for these cargoes.

These old site diagrams were formed by initially drawing up pencil sketches on-site, when the environment was being surveyed and excavated. Later, the sketches were redrawn through a computer-aided software. Templates of the object of interests (e.g. the amphora) were created based on the previously measured archaeological sketches with a scale and catalogue pages. These templates where then angled over the pencil so that distinct points (e.g. toe and mouth of an amphora) fit within the same placement as on the pencil plan, which produced an overall sketch of the environment. Figure 1 shows a site diagram for the amphora mound discovered at the start of the excavation. Figure 2 shows another site diagram showing the millstones that were discovered during the middle of the excavation.

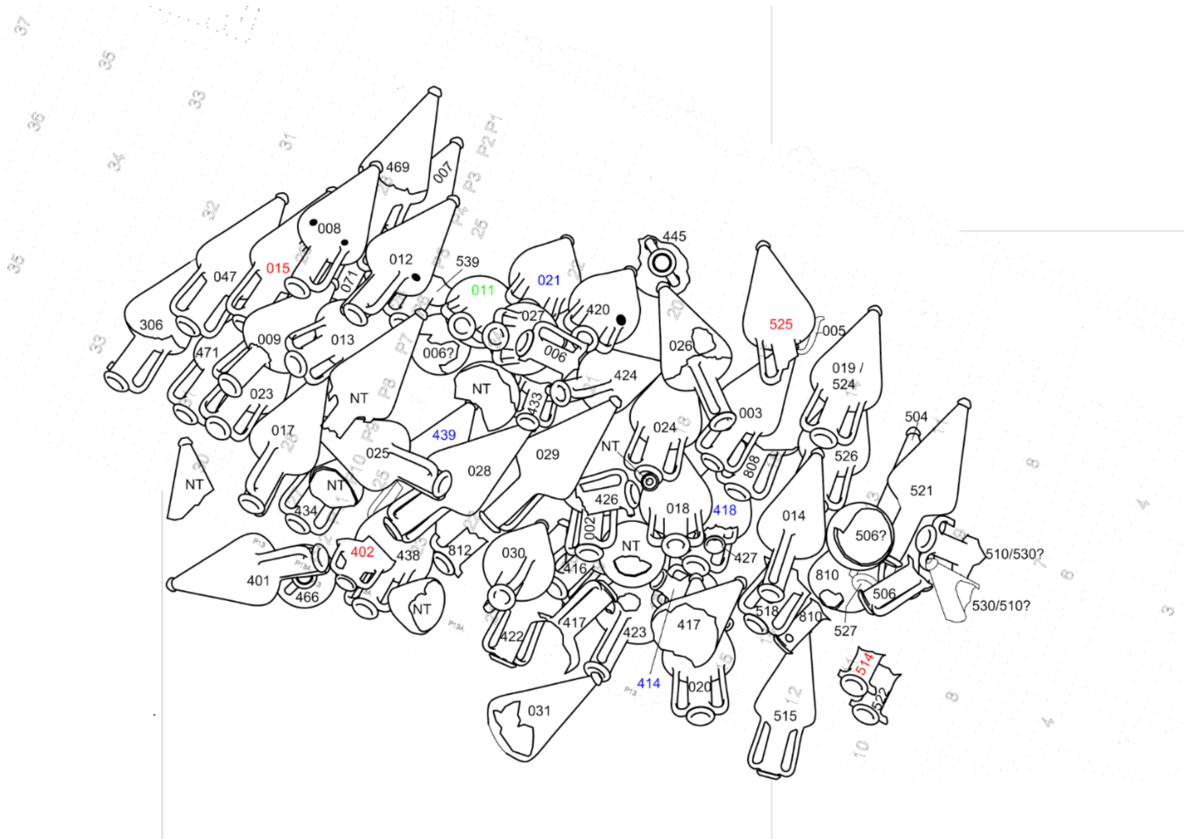

Figure 1: Section from amphora site diagram

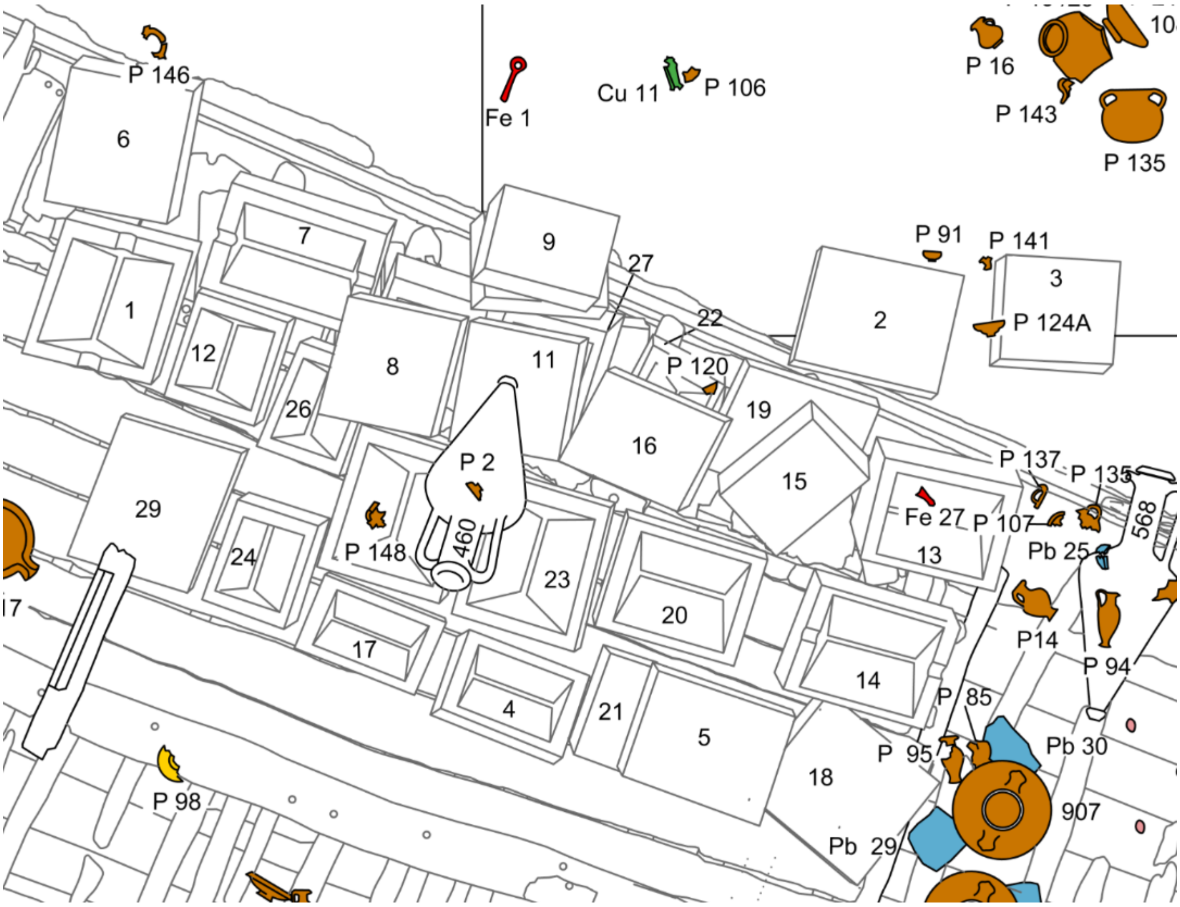

Figure 2: Site diagram for the millstones

Additional data was taken during the excavation; a large number of 2D photographs of the site were taken across different days. The films have been scanned but had not been used to recreate site plans. An initial test on a set of images showed that it is possible to create digital 3D models, through photogrammetry.

1.2. Project Objectives

This project involves photogrammetric reconstruction of the 4th century BC Kyrenia shipwreck and aims to verify the measurements of the original site diagrams of the Kyrenia shipwreck site using information from a reconstructed 3D environment. To achieve this, the following tasks are required:

- Reconstruction of a 3D model from images taken on-site
- Deriving an orthographic projection (top-view) image from the 3D model
- Comparison of the ortho image and the site diagrams

The project concentrates on three environments in different times:

- The amphora mound in 1967 before the excavation
- The grindstones exposed in 1968
- The exposed amphora and grindstones exposed in 1969 with part of the hull structure

1.3. The HIVE internship program

This project was conducted as part of the Curtin University HIVE Summer Internship Program (2019-20). We appreciate financial and technical support from Susan Katzev, and technical support from the Western Australian Museum. The Curtin HIVE Summer Internship Program allows a Curtin student to undertake a 10 week full-time internship to undertake a research project investigating the application of visualisation technologies to a particular discipline area. Interns had regular access to the Curtin HIVE, were supported by the HIVE staff, and were supervised by a discipline leader. The results of the HIVE Summer Intern projects were presented at the HIVE Summer Intern Showcase held at the Curtin HIVE on Friday, 14th of February 2020, and also presented in a written report (this report).

2. Background

2.1. How the original site diagrams were produced

The Kyrenia shipwreck environment was originally documented by creating a pencil sketch. The following is a summary of how a pencil sketch was produced for the hull of the Kyrenia shipwreck (Höhle, 1971):

1. A "stereometric" double camera was used to generate a stereo pair of photographs (see Figure 3).
2. The films were oriented onto a "Stereotope", an instrument that projects and reconstructs the environment as an optical model, through the use of a light marker that can be measured by position and height (see Figure 4).
3. The optical model was traced on paper to formulate the pencil sketch.

Figure 3: Underwater operation of the stereometric double camera (Höhle, 1971)

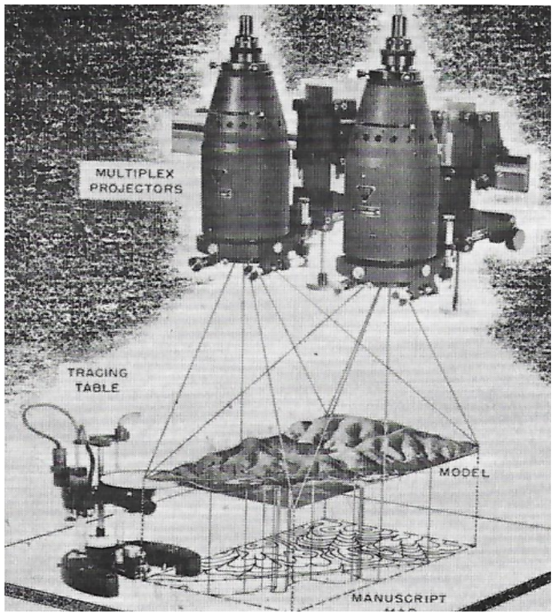

Figure 4: How the environment is projected by the stereo images (Höhle, 1971)

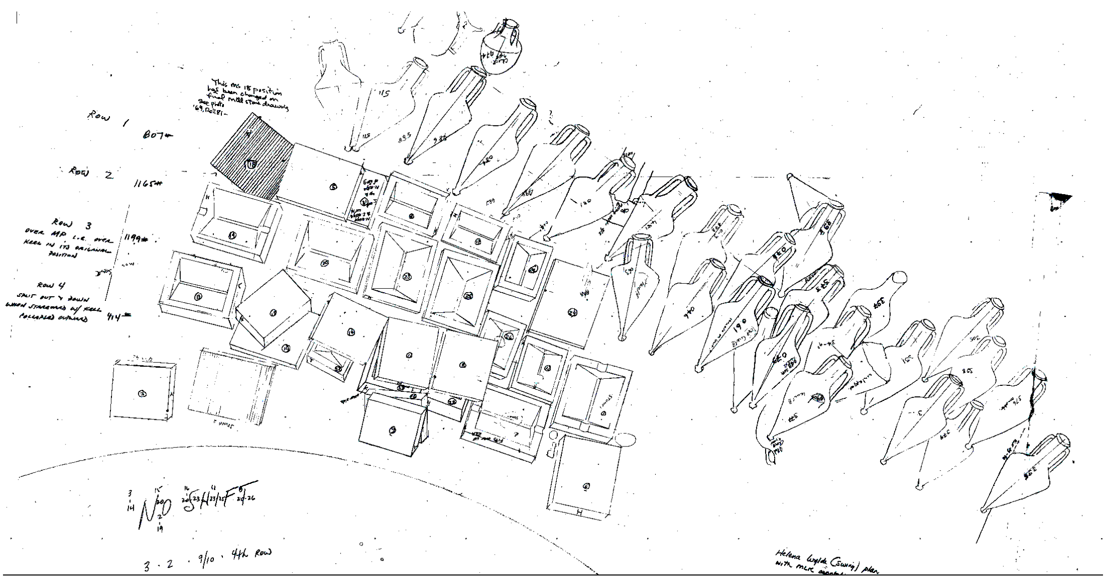

Figure 5: Pencil plan example of millstones and amphora

As for the amphora and millstones, it is reasonable to infer that a similar method to the ship's hull was performed. Figure 5 illustrates an example of a pencil sketch for the amphora and millstones, representing the excavated site in 1969.

Additionally, each millstone, as a single entity, was measured and sketched on site.

Then, to recreate the plans digitally, templates for the amphorae and millstones were used. Each digital object was created based on the template and then repositioned and angled to 'trace' the environment based on the pencil sketch. This method produced digital sketches, as shown in Figure 1 and Figure 2, which are the site plans that will be used for comparison with the results of this project.

2.2. Uncertainties of the measurement of the site diagrams

The pencil plans and digital sketches have some uncertainty involved in its measurements, as the creation of these plans were estimated. For example, exact and detailed measurements of the overall millstone environment could not be sketched on site, due to underwater constraints. However, the millstone dimensions provide a reference for measuring the overall environment. Thus, a drawing with measurements can be formulated.

Nevertheless, the single millstone dimensions do not account for the projection of each millstone with respect to the whole environment, as when viewed on a map. The repositioning and angling of the millstone templates (as conducted in the digital recreation) help with orienting the millstones and accounting for the projection, however these are still based on approximations, e.g. the orientation of the millstones had to be guessed.

Therefore, there may be merit to using photogrammetry on the legacy photos to create a 3D model and then an orthomosaic map, to verify the original site diagrams.

2.3. Agisoft Metashape

Agisoft Metashape is a commercial software product that performs photogrammetric processing of images to generate 3D spatial data (digital 3D models). This is widely used in geographic information system (GIS) applications and cultural heritage documentation (Agisoft, 2019). Relevant features include the ability to perform masking on images, aligning photos, generating point clouds, generating meshes, generating textures for the mesh to create a digital 3D model, and generating orthomosaic maps. For this project, version 1.5 of Metashape (Standard Edition) was used.

2.4. QGIS

QGIS is a free and open-source software product that allows creation, editing, visualisation, analysis, and publication of geospatial information (QGIS, 2020). With QGIS, a researcher is able to perform overlay of images and error analysis between the overlaid images. QGIS version 3.10.1 (*A Coruña*) was used for this project.

3. Methodology

The project focussed on three different areas, which is summarised in Table 1.

Table 1: Overview of the processed data sets

Area	Excavation year	Scene content	Reference diagram
1	1967	Amphora mound	Figure 1
2	1968	Millstones	Figure 2
3	1969	Millstones	Figure 2

For each area, a 3D model was reconstructed from the photos, an orthomosaic map was derived, and then the orthomosaic map was compared to the relevant site diagram for verification.

3.1. 3D reconstruction of the scene and deriving the orthomosaic map

The selected images were pre-processed to improve the aesthetics of the resulting textured 3D models. Histogram stretching was performed on the images. Although this process is not needed for the 3D reconstruction (image alignment and point cloud generation) stages of the processing, it has been found to improve the quality of the generated textures.

The images were then fed into Agisoft Metashape, in which the following workflow was carried out:

1. Masking was performed to isolate the relevant section of the image (and remove irrelevant areas), thereby eliminating the foreground (e.g. grid frames) and non-static objects (e.g. fish). The masking process was done by manually adding bounds, which the program will exclude when reconstructing the model. This step was required as the foreground objects would contribute a large number of outliers to the matching process leading to inaccuracies and sometimes even making it impossible to process the data successfully.

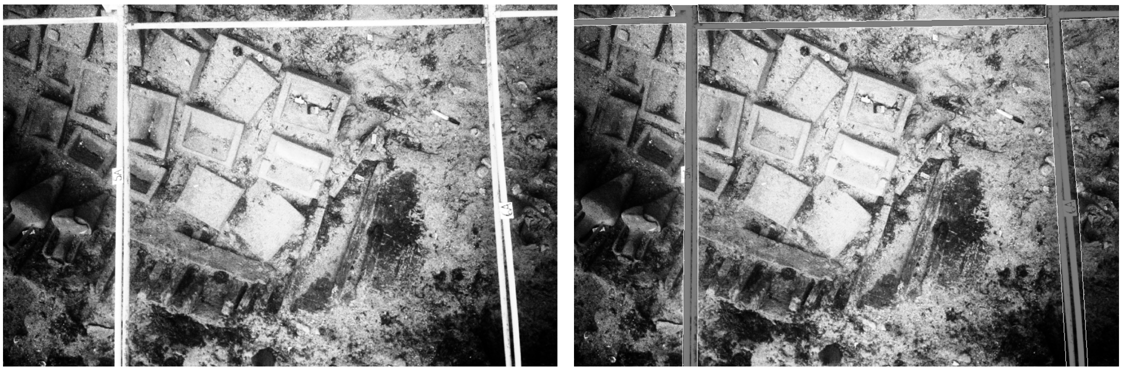

Figure 6: Unmasked image (left) vs masked image (right). The bright white section in the left image are a grid frame which unfortunately is not solid and moves between photographs.

Figure 6 illustrates how the masking 'bounds' appear in Metashape. The masked image shows a darkened area that corresponds to the grid frames, which were unwanted in the final 3D model and ignored my Metashape.

2. The masked images were then aligned through the function 'Align Photos' using the settings of:

    - Accuracy: Highest
    - No Generic Preselection
    - Key point limit: 80000
    - Tie point limit: 20000
    - Apply masks to: Key points

   Upon alignment, a sparse point cloud is generated. The sparse point cloud essentially consists of sets of points/features that at least three images have in common. Figure 7 shows an example of a sparse point cloud of the 1969 millstone environment, where 13 out of 15 images had been aligned.

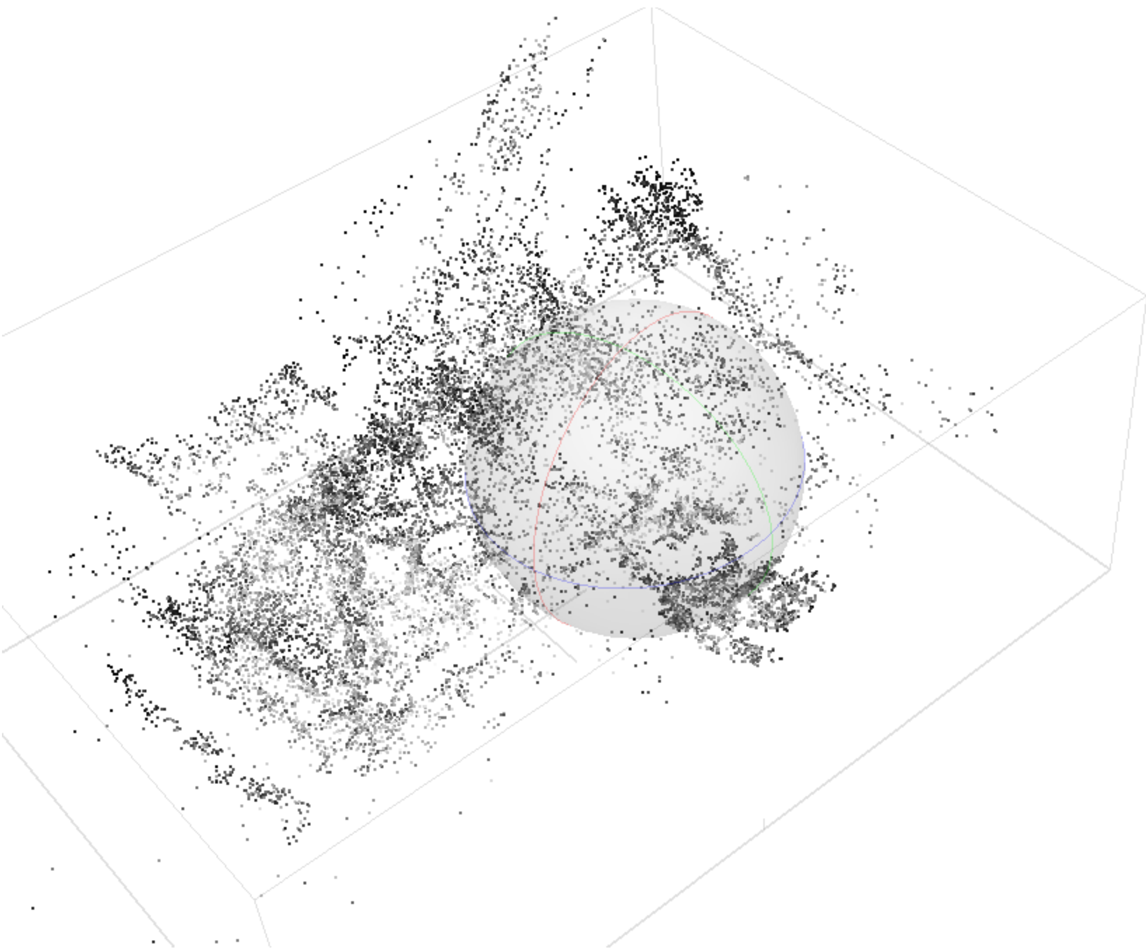

Figure 7: A sparse point cloud of the 1969 millstone environment showing tie points across the 13 aligned images

3. The images were then optimised (fitted) to account for distortions. The ‘Optimize Cameras’ function was performed. The parameters that were optimised are as follows: *f, cx, cy, k1, k2, k3, b1, b2, p1, p2*.
4. The dense cloud and mesh were then created using the functions ‘Build Dense Cloud’ and ‘Build Mesh’, respectively. Figure 8 and Figure 9 illustrates the dense cloud and the mesh (3D model). The settings used are as follows:
   - Dense Cloud:
     - Quality: Ultra High
     - Filtering Mode: Mild
   - Mesh:
     - Source data: Dense cloud
     - Surface type: Arbitrary (3D)
     - Face count: High

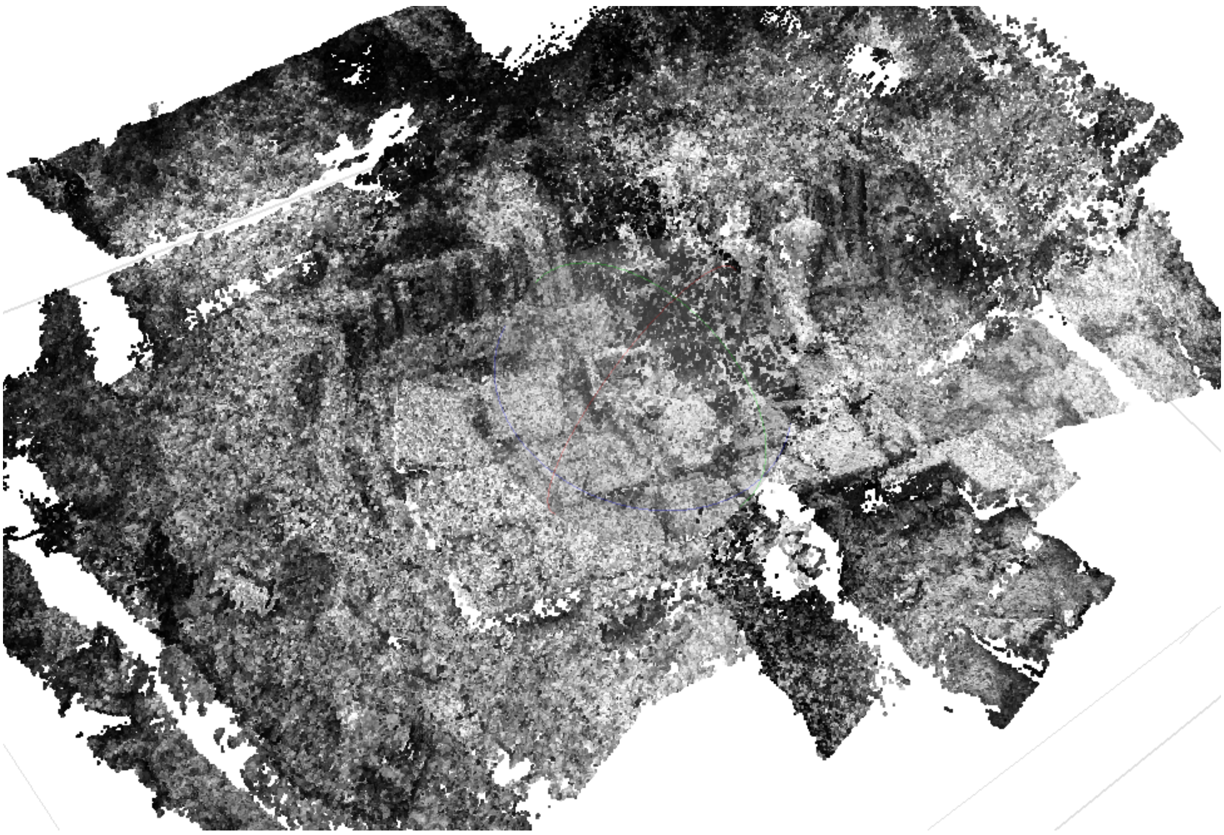

Figure 8: Dense cloud of the 1969 millstone environment

Figure 9: The 3D model (mesh) with shaded vertex colours for the 1969 millstone environment

5. To represent the reconstructed environment more realistically and improve aesthetics, texture was added to the mesh. The 'Build Texture' function was used. Figure 10 illustrates the textured version of the mesh. The settings used were as follows:

    - Mapping mode: Generic
    - Blending mode: Mosaic
    - Texture size: 4096
    - Enable hole filling: Yes
    - Enable ghosting filter: Yes

Figure 10: The textured version of the mesh for the 1969 millstone environment

6. An orthomosaic map, which is a top view projection of an environment, was then derived from the 3D model. The orthomosaic map makes it easier to perform measurements, thus allowing comparison of the model to the site diagram. The 'Build Orthomosaic' function was used in Metashape, where the projection type is 'Planar', and the projection plane is 'Top XY'.

3.2. Overlay of the original site diagram to the orthomosaic map

To allow for comparison between the results and the reference site diagrams, the reference site diagrams were overlaid onto the orthomosaic maps.

Due to differences in coordinate reference systems and centre point of the projection, the site diagram must be reprojected onto the orthomosaic map. Therefore, image transformation was performed on the site diagram to account for this difference, through the software QGIS. The transformation type applied was projective accounting for the different points of views from which the maps were taken.

The overlaid site diagram was then made semi-transparent in order to see the overlay.

3.3. Vector dataset creation

For the millstone images, the site diagram and the orthomosaic image were ‘digitised’, i.e. converted to vector shapes, to demonstrate the overlay more clearly.

Using QGIS, a vector layer was added to the orthomosaic map so that shapes can be traced onto the image and hence creates a simplified diagram that best represents the environment. The same was performed to the original site diagram, although only including the parts that are relevant and can be compared to the ‘digitised’ version of the orthomosaic map.

4. Results

4.1. Orthomosaic Maps

The following images are the resulting orthomosaic maps derived from the 3D models. Refer to Figure 11 for the 1967 amphora mound, Figure 12 for the millstone environment in 1968, and Figure 13 for the millstone environment in 1969.

Screenshots of the 3D models from which the ortho-maps were derived are attached in the Appendices.

Figure 11: 1967 amphora mound orthomosaic

Figure 12: 1968 millstones orthomosaic

Figure 13: 1969 millstones orthomosaic

Discussion

Agisoft Metashape has successfully generated 3D models and orthomosaic maps of the environments.

Overall, the reconstruction is detailed enough to verify site diagrams. However, there are a few errors. One example is in Figure 13, where there is an evident ‘hole’ on the reconstruction of the millstone. This is attributed to the lack of alignment of certain photos and Agisoft Metashape ignoring these photos in the reconstruction process. Nevertheless, the overall picture of the 1969 ortho-map in Figure 13 is satisfactory.

4.2. Site diagram overlays and digitised versions

Figure 14, Figure 15, and Figure 16 show the overlay of the site diagram, which is the semi-transparent line drawing (foreground), on the orthomosaic map (background), for the 1967, 1968, and 1969 environments, respectively.

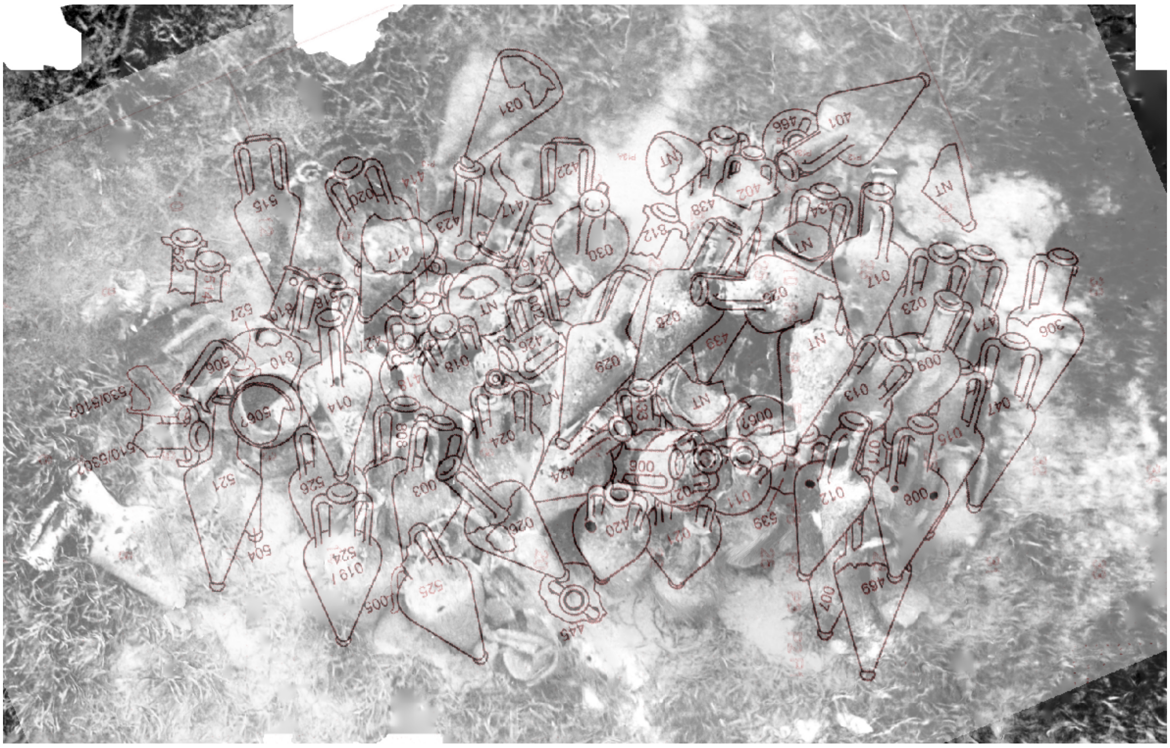

Figure 14: 1967 amphora mound site diagram overlay. The greyscale image is the orthomosaic generated in this project, and the red lines are the original site drawing from the 1970s.

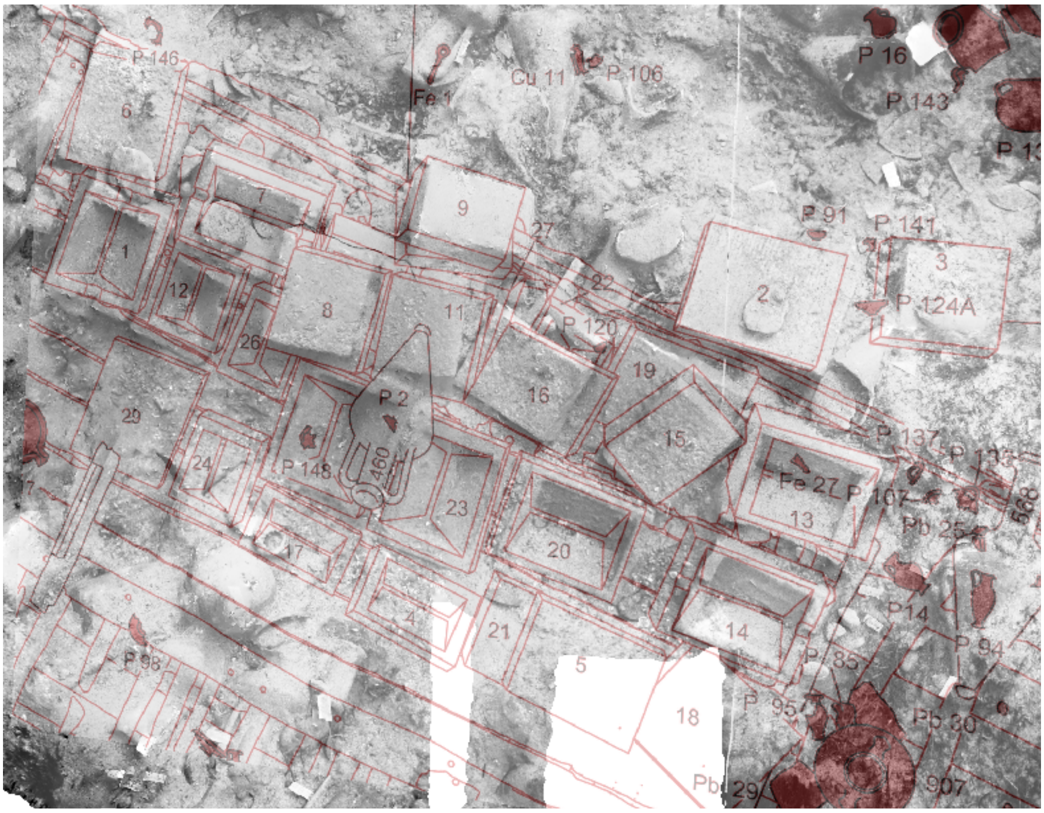

Figure 15: 1968 millstones site diagram overlay. The greyscale image is the orthomosaic generated in this project, and the red lines are the original site drawing from the 1970s.

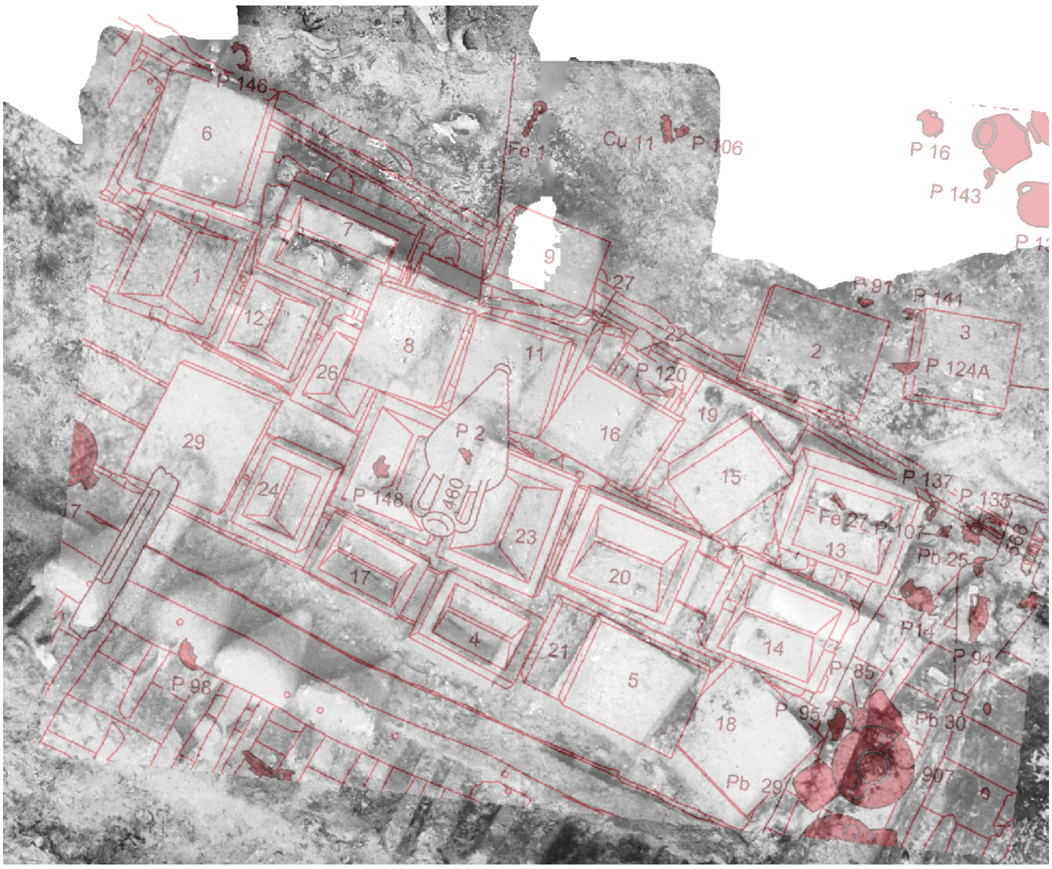

Figure 16: 1969 millstones site diagram overlay. The greyscale image is the orthomosaic generated in this project, and the red lines are the original site drawing from the 1970s.

Figure 17 and Figure 18 show the 'digitised' version of the overlay of the millstone environments for both the orthomosaic map and the site diagram, for 1968 and 1969.

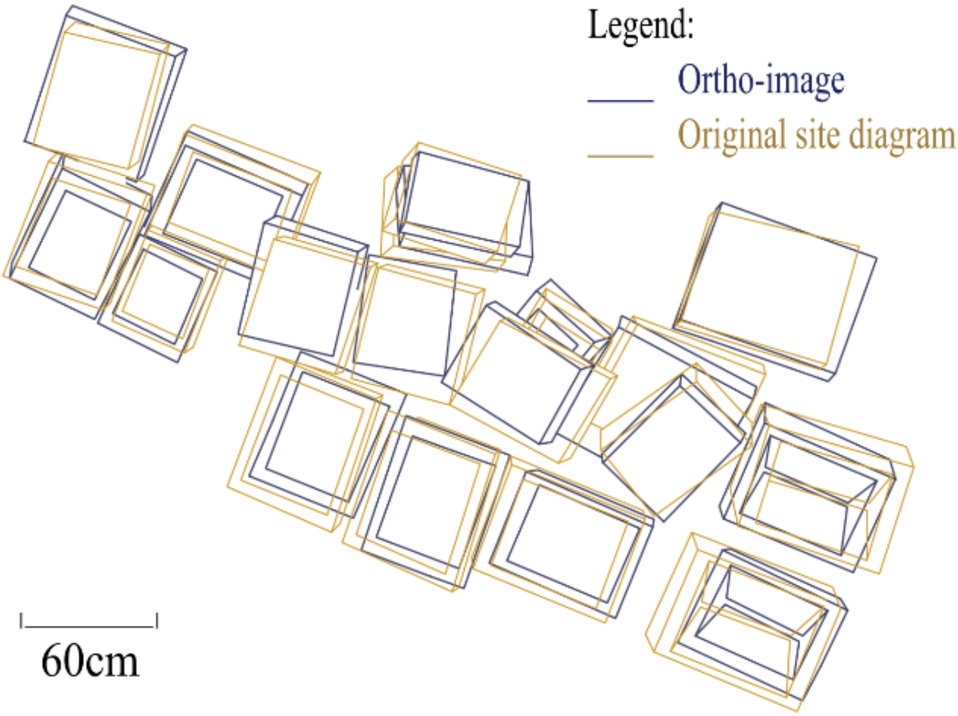

Figure 17: Digitised version of the overlay for the 1968 millstone environment

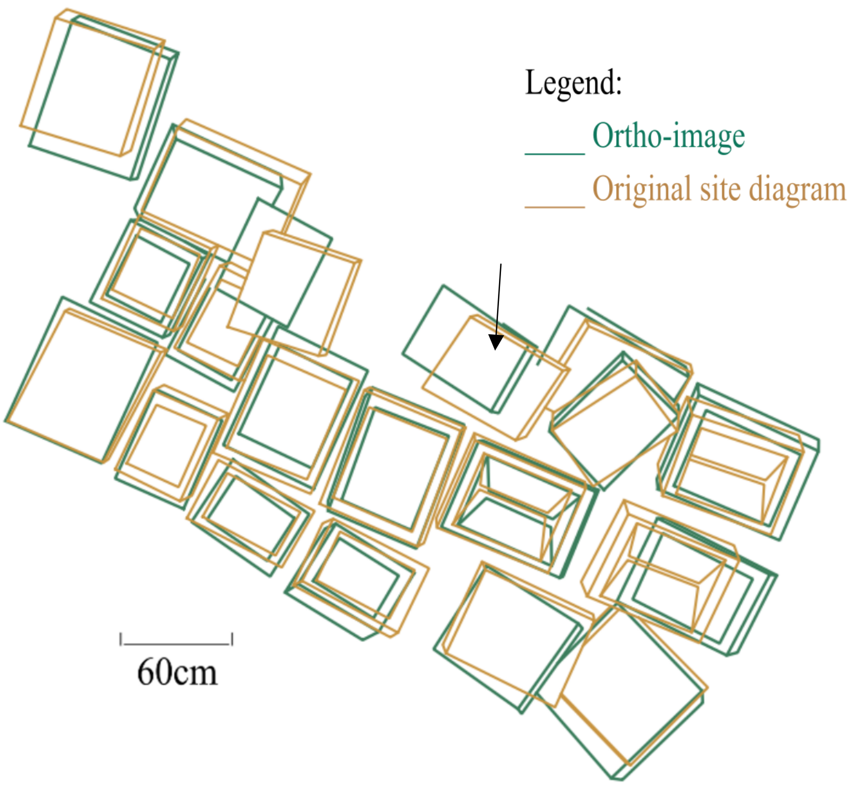

Figure 18: Digitised version of the overlay for the 1969 millstone environment

Digitising the amphorae was a challenge due to the complexity of its shape. Moreover, in the 1967 amphora mound (refer to Figure 11), the amphorae are often overlapping and broken, thereby making it difficult to produce a diagram via tracing.

Discussion

For the 1967 amphorae, as shown in Figure 14, there are amphorae that almost fit the overlay, such as those labelled '025' on the right section of the map and '525' on the bottom section. However, there are amphorae that seem to have been displaced, such as '521' on the bottom-left. This may be attributed to dynamic environmental factors, i.e. the amphora may have been moved. There are also amphorae that are missing in the orthomosaic map that are present in the site diagram. This may have been due to the fact that some of the amphorae have not been completely uncovered or that they were been removed before the photography.

For the 1968 millstones, overall, the millstones in the ortho-image fit the ones from the site diagram (Figure 15 and Figure 17). Differences in position and orientation are evident, but seem to be reasonably small.

One interesting element is the millstone on the bottom right in Figure 17, where it can be seen that the millstone in the drawing has different dimensions to the orthophotograph. This was probably because in the 1968 plan, the millstone were drawn with templates for the different types of millstone, and in this case the the wrong template was applied.

There are also millstones that are present in the site diagram but missing in the ortho-image image, such as the bottom row of millstones in Figure 15. This is because the bottom row of millstones had not been excavated at the time the photographs were taken in 1968.

Similarly, the 1969 millstones in the ortho-image fit with the ones in the site diagram (Figure 15), although there are some differences in position and orientation. One notable difference is labelled with an arrow in Figure 15, where the difference is significant. This may have been because the millstone had moved slightly.

There are also millstones that are not present in the orthomosaic image, but present in the site diagram, such as Millstones '1' and '2'. These millstones may have been removed from the site before the photography.

Furthermore, although present in the orthomosaic image (Figure 16), some millstones were excluded in the digitised version (Figure 18), such as Millstones '3' and '9' in Figure 16. This was due to artefacts in the reconstruction for the zones where these millstones are, which made it difficult to determine the shape when tracing.

4.3. Error analysis

From the digitised version of the overlay, error analysis was then performed to quantify the differences. To achieve this, one digitised map (i.e. original site diagram) was selected to undergo transformation such that it fits the other digitised map (i.e. ortho-image). The transformation produces residuals, which quantify how far the transformation was performed onto the image. From the residual of each point, the root mean square error (RMSE) was then obtained, which is the overall quantity describing the difference between the orthomosaic map and the site diagram.

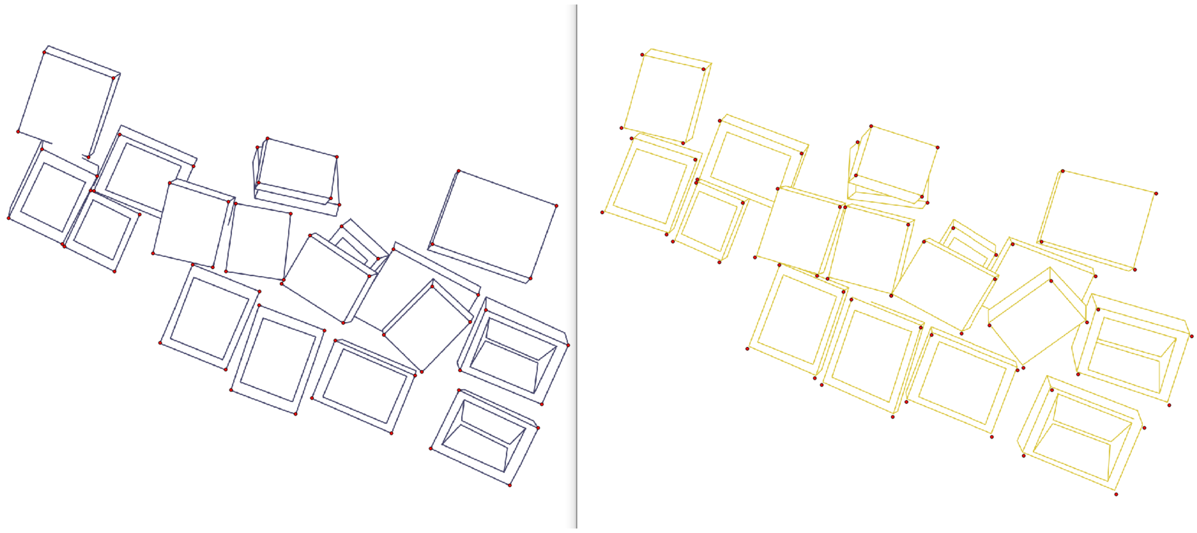

Figure 19: Feature points for the transformation of the 1968 site diagram (yellow) to the orthomosaic image (blue)

For the millstones, the corners were selected as feature points for this transformation. Helmert transformation was used, to account for rotation, scaling, and translation. Figure 19 shows an example for the 1968 millstone diagrams. Each specific corner of a millstone in the site diagram (yellow) was referenced to the corresponding corner in the orthomosaic map (blue). The transformation then corrects these differences in distance and produces a set of residuals for each point from which the RMSE can be obtained.

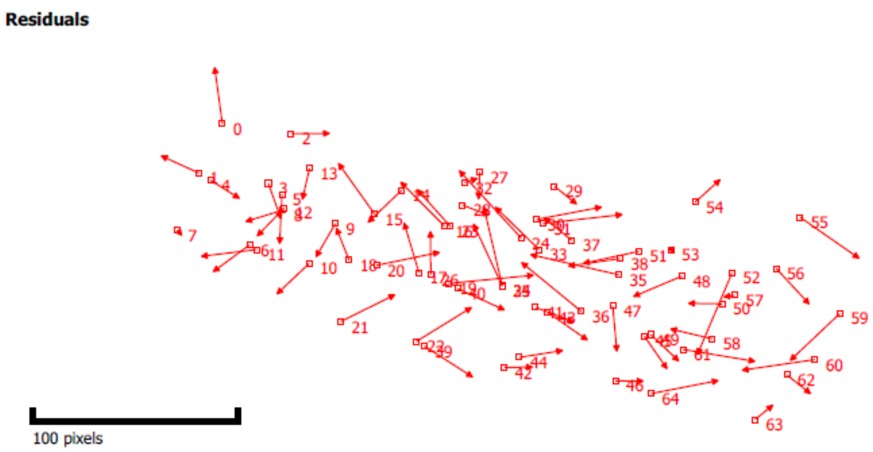

Figure 20: Residual map for the 1968 millstone environment

Figure 20 shows arrows indicating the magnitude (in pixels) and direction of the residuals for each corner of the millstones. The transformation was successful, as the errors are random, all with the same magnitude; systematic errors are not apparent.

From this, the overall transformation parameters, including the RMSE, was obtained. The RMSE was then converted to centimetres based on the given dimensions of the millstones from the original survey.

The same method was performed for the error analysis of the 1969 millstones.

For the 1967 amphora, the diagrams were not digitised due to its complexity. Therefore, the tips of the toe and the end of the mouth of the amphorae were 'marked' and selected as feature points for the error analysis.

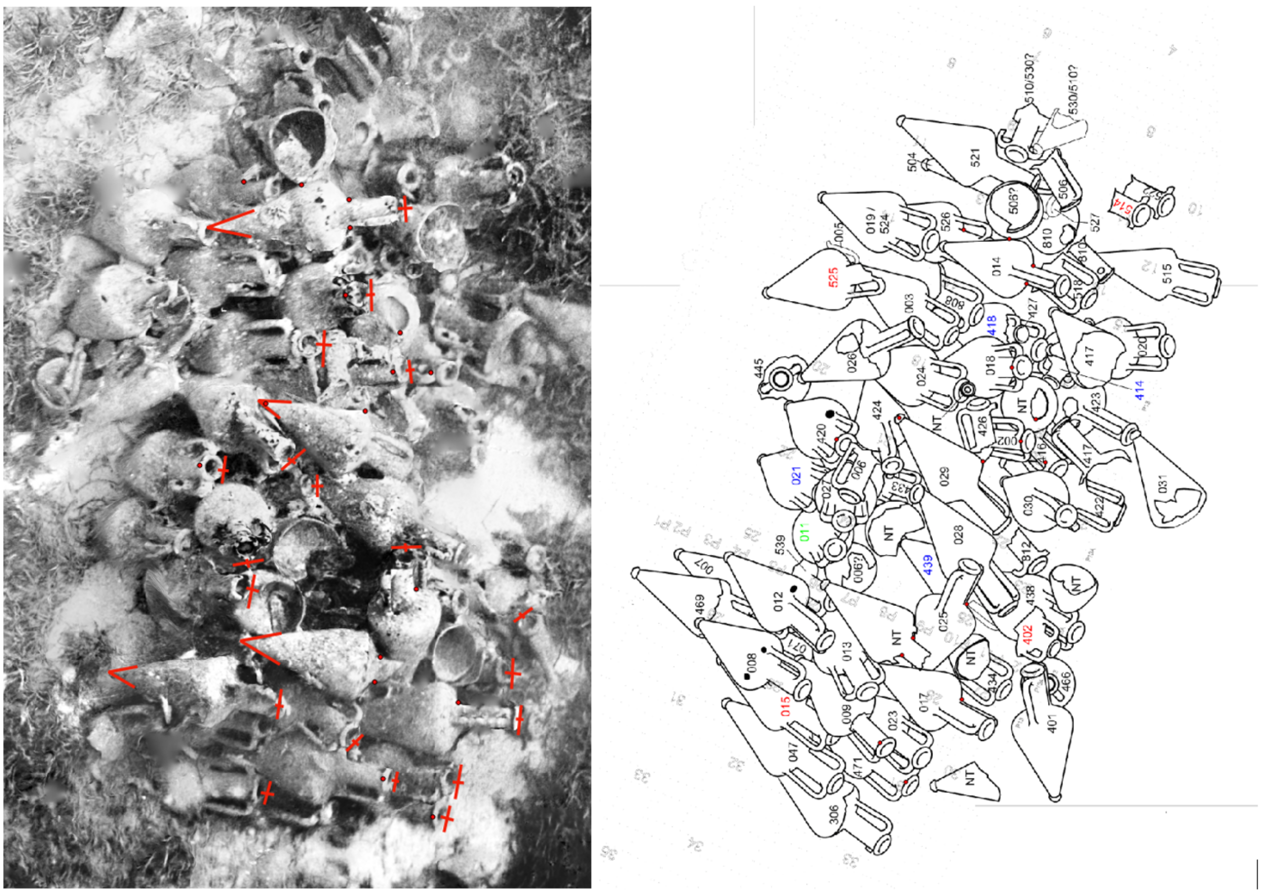

Figure 21: Feature points for the 1967 amphora error analysis

Table 2 summarises the resulting transformation parameters for the error analysis for each environment. The translation, scale and rotation parameters indicate the degree to which the site diagram was transformed around the QGIS workspace.

The translation parameters for the 1969 millstones are very high, however these merely indicate that the distance between the 2 diagrams were very far from each other initially, at the start of the comparison. These are 'normalized' during the transformation process.

Table 2: Translation parameters of the error analysis

	Translation x (px)	Translation y (px)	Scale x	Scale y	Rotation (degrees)	Mean error (px)
1967 Amphora	-477.379	102.604	1.69266	1.69266	0.825871	**19.9376**
1968 Millstones	8.323	-6.420	0.991445	0.991445	0.178672	**25.9848**
1969 Millstones	1340.005	-2154.658	1.91573	1.91573	-0.102602	**27.3239**

More importantly, the mean error data in Table 2 show the RMSE, in pixels.

The converted RMSE, in centimetres, for each area is summarised in the following table. The environment size is also included for comparison. For the 1967 amphorae, the environment size was given (Green, et al., 1967). For the 1968 and 1969 millstones, the environment size was estimated based on the millstone sizes.

Table 3: RMSE quantities for the error analysis of the overlays

Area	RMSE (cm)	Environment Size
1967 Amphora	4.31	3m x 5m
1968 Millstone	7.43	5m x 2.5m
1969 Millstone	4.38	5m x 3m

For each environment, the RMSE is small when compared to the environment size.

4.4. Summary

Overall, the orthomosaic maps generated from the 3D model (Figure 11, Figure 12 and Figure 13) satisfactorily represent the corresponding site diagrams with reasonable accuracy, as evident from the overlays (Figure 14 to Figure 18) and the RMSE values in Table 3: RMSE quantities for the error analysis of the overlays Table 3.

Therefore, the measurements of the original site diagrams of the Kyrenia shipwreck can be verified using information from a reconstructed 3D environment. It is feasible to use photogrammetry to verify site diagrams and even create them, with a potentially higher accuracy.

5. Conclusion

This project successfully generated detailed digital 3D models and orthomosaic maps for the 1967 amphora mound, 1968 millstones and the 1969 millstones.

The detailed digital 3D models can be useful for creating visually realistic depictions of the site for developing virtual heritage experiences, possibly using Virtual Reality (VR) simulations or 3D printing. Virtual models were uploaded on Sketchfab (see Appendices).

More importantly, the comparison of the orthomosaic maps to the original site diagrams showed a satisfactory fit. Additionally, error analysis of the overlays resulted in RMSE values of 4.31cm, 7.43cm and 4.38cm for the 1967, 1968 and 1969 environments, respectively. These are reasonable quantities, particularly when compared to the overall environments which span several square metres.

It can be deduced that the measurements of the original site diagrams of the Kyrenia shipwreck can be verified using information from a reconstructed 3D environment. It is therefore feasible to use photogrammetry to verify site diagrams or to create them at a potentially higher accuracy.

5.1. Challenges encountered

Some challenges encountered in this project are as follows:

- Masking was a time-intensive task, as one needs to uniquely create a mask for each image. This is particularly difficult for applications with large image datasets. Future work may include creating a machine learning algorithm that performs automatic masking, so as to eliminate the need to perform this time intensive task.
- Some photos would not align despite the fact that they were good quality and had good image overlap. For some unknown reason Metashape ignores some good photos. The addition of manual markers to 'force' alignment was attempted, however, they were unsuccessful.

5.2. Assumptions and premises

The analyses and conclusions deduced from this report operate on the following premises:

- The orthomosaic image was selected as ground truth when comparing the two maps. This assumes that the 3D reconstruction is perfect and contains no spatial errors.
- In the RMSE analysis, it was assumed that the chosen feature points (i.e. toe and mouth of amphora, top and outer corners of millstones) are sufficient to quantify the differences in distance for the whole environment. There were details that were conveniently ignored, such as bottom corners of millstones (which also influences the overall measurements of the environment).

5.3. Archaeological significance

From an archaeological point of view the results of this project have been extremely interesting. Firstly, this is the earliest excavation where it has been possible to return to legacy data and obtain 3D records of the site. No doubt the study of the photography of the hull of the ship will be extremely interesting and this project indicates the potential of this approach. Other studies of legacy data have included a tile wreck site at Cape Andreas recorded in 1970 (Green, 2019) and the Hull of the Portuguese frigate *Santo António de Tanná* (1697) in Mombasa, Kenya excavated between 1977 and 1980 (Shaw, 2018).

The ability to return to archaeological excavations projects where photography played an important role has considerable significance in the ability to reassess the excavation work. This project that took place over 50 years ago is really significant. It shows that much of the methodology used at the time, whilst rather crude, produced reasonable results. On can see where small mistakes and discrepancies have occurred in the original survey plan, but on the whole to original results are good.

The methodology will provide opportunities in the future for archaeologists to reassess legacy data. In some cases, where site plans were not made there will be an opportunity to produce such plans.

6. Acknowledgements

I would like to thank the following people for all the support and help they have given during the project:

- Petra Helmholz for the academic knowledge you have shared and the kindness and support you have provided during difficult times, along with presenting my project in the HIVE Summer Intern Showcase
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- Jeremy Green for providing the resources needed to make this project possible, for the insight during the meetings, and for the wonderful stories of your experience in the Kyrenia shipwreck excavation
- Daniel Adams for the technical support in installing the HIVE computing facilities and for post-processing some of the 3D models for uploading purposes
- Carley Tillett for helping me organise my project better
- Susan Katzev for providing financial and technical support for the internship.

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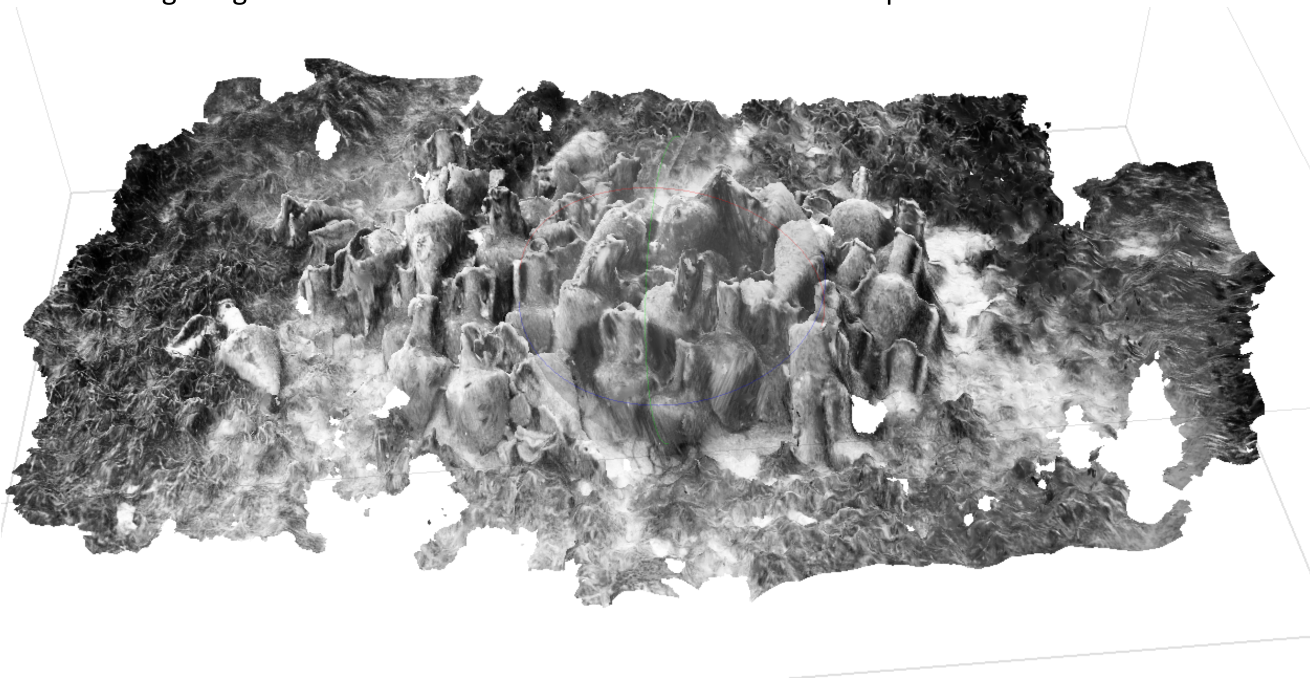
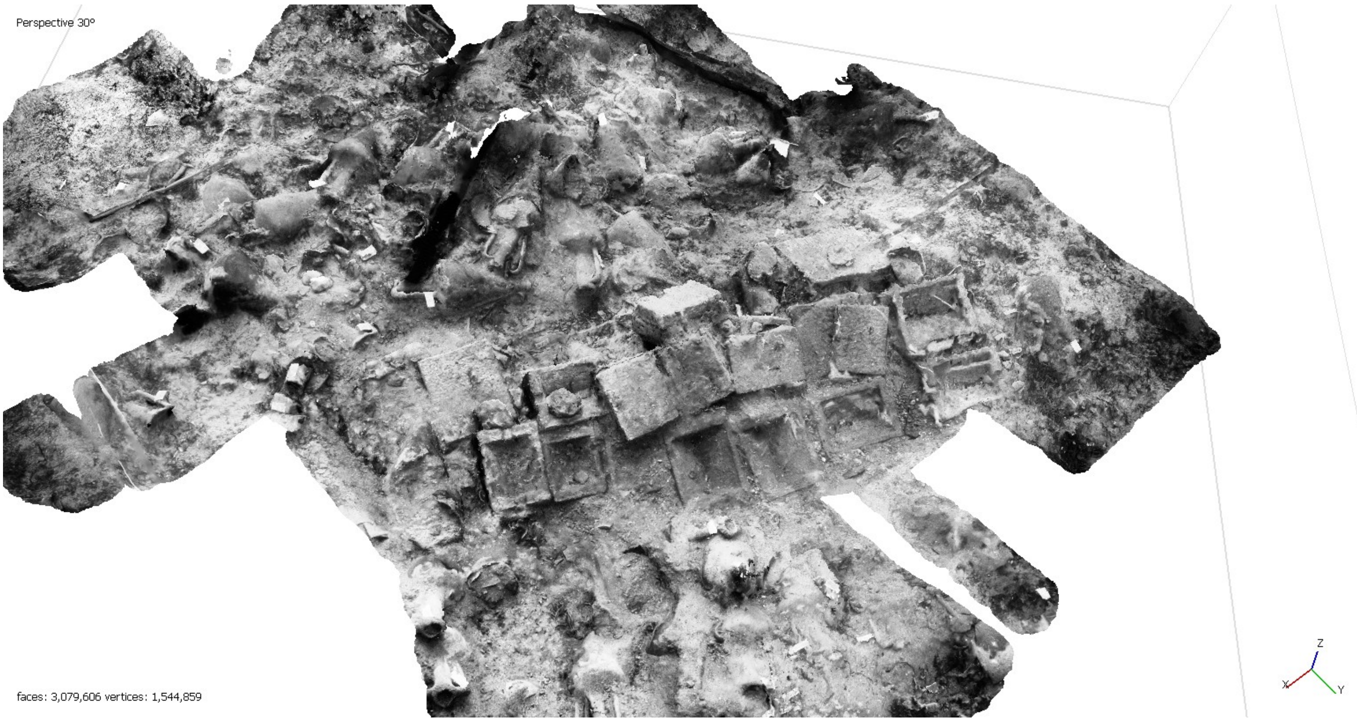
8. Appendices

The following image is a screenshot of the 3D model of the 1967 amphora environment:



An interactive digital 3D model is available at the following URL: https://sketchfab.com/3d-models/1967-amphora-2da376cf7d1a4a9bb558707a8023b2e5. However, the mesh count is reduced, compared to the Metashape model shown above.

The following image is a screenshot of the 3D model of the 1968 millstone environment:



An interactive digital 3D model is available at the following URL: https://sketchfab.com/3d-models/1968-millstones-f53b4746bd7a4b06bbfcc888d86c2f65. However, the mesh count is reduced, compared to the Metashape model shown above.

The following image is a screenshot of the 3D model of the 1969 millstone environment:

An interactive digital 3D model is available at the following URL: https://sketchfab.com/3d-models/1969-millstones-ffb69ba81ec344a9a39d215e4b3e7f7c. However, the mesh count is reduced, compared to the Metashape model shown above.