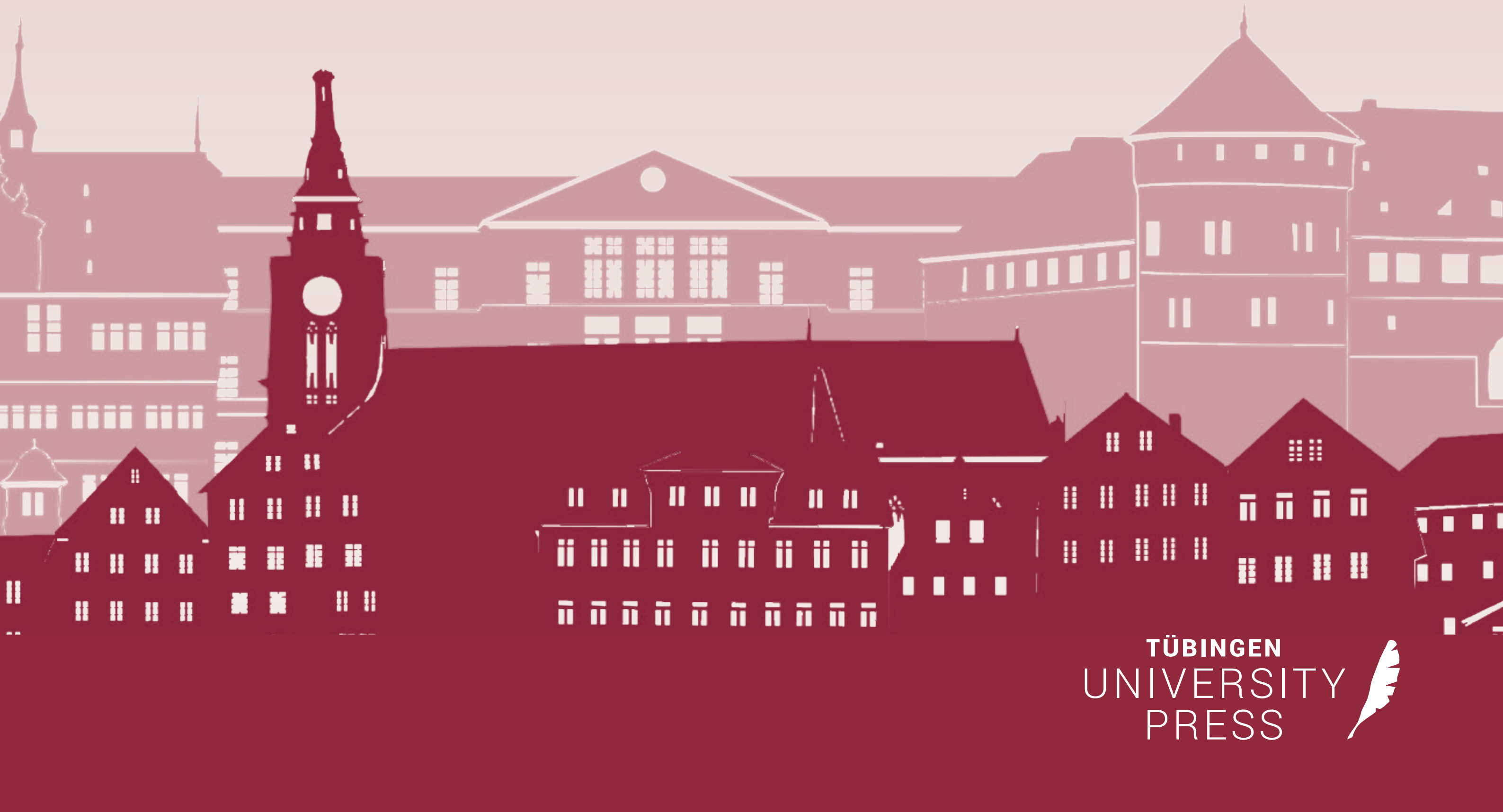
CAA 2018

HUMAN HISTORY AND DIGITAL FUTURE

PROCEEDINGS OF THE 46TH ANNUAL CONFERENCE ON COMPUTER APPLICATIONS AND QUANTITATIVE METHODS IN ARCHAEOLOGY

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

EDITED BY
MATTHIAS LANG, VOLKER HOCHSCHILD, AND TILL SONNEMANN



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Human History and Digital Future

Proceedings of the 46th Annual Conference on Computer Applications and Quantitative Methods in Archaeology

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Introduction

The proceedings represent a cross-section of the papers and posters presented at the 46th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA) in Tübingen. With over 450 attendees and 420 papers in 40 sessions, it was one of the CAA's largest conferences.

The topic of CAA 2018 is "Human History and Digital Future", which we represent with the famous Ice Age wild horse from the Vogelherd Cave, not far from Tübingen. The small ivory carving is one of a whole series of ice-age sculptures, which belong to the oldest works of art of mankind. With this topic and logo, we hope to capture the essence of the rich archaeological landscape of southwestern Germany, while at the same time highlighting our responsibility in preserving the cultural heritage of humankind for future generations using pioneering digital methods and tools.

The conference began with thirteen workshops covering the full spectrum of digital archaeology. The traditional icebreaker party took place in the old auditorium of the university and was an opportunity to meet old friends and make new ones.

The first day of the conference proper began with a keynote address by Gunter Schreier, the deputy director of the German Remote Sensing Data Center, who presented the European Copernicus program and outlined how freely available remote sensing data can help protect tangible cultural heritage.

Afterwards, the participants presented and discussed the results of their research on almost all relevant topics of digital archaeology in eight parallel sessions. The first full day concluded with a reception at Hohentübingen Palace, home to the archaeological collections of the University of Tübingen. All rooms were open to the participants and drinks and snacks were served.

On the second day of the conference, the CAA traditionally held its annual meeting, which was followed by the conference dinner. We decided against a formal dinner and instead had a Bierfest with traditional German food, drinks and live music.

Like the previous days, Thursday was filled with eight simultaneous sessions and ended although no social program was planned for the evening, countless participants found themselves in a traditional pub in Tübingen's old town that has probably rarely sold such quantities of beer in one evening.

The excursion after the conference took the participants to some of the most exiting archaeological sites of Europe including the Swabian Ice Age caves, the Neolithic lake dwellings on Lake Constance, and to the Celtic hillforts on the Swabian Jura.

For us it was a great honor to welcome so many guests from all over the world in our small town and hope that everyone took home new ideas and new friends.

Matthias Lang, Volker Hochschild

Acknowledgements

From the first plans to host the conference in Tübingen to the completion of the proceedings it has been a long way, and so it is difficult to remember all those who made the success possible. Nevertheless, we would like to express our gratitude to all those who have supported us tirelessly.

A first thank you must go to the Scientific Committee. Paul Reilly supported us in endless Skype conversations and was an immense help in planning the event. No less appreciation goes to the Steering Committee, which was always available for us and helped to identify and solve many problems at an early stage.

We would like to thank Hembo Pagi for the maintenance of the homepage and the quick solution of problems related with it.

Without the help of our colleagues in Tübingen, the organization of such an event would of course never have been possible. We would like to thank all of them for the time they spent on the organization of the CAA. In addition to Geraldine Quénéhervé, Michael Märker, Philippe Kluge, Andrew Kandel, Vinzenz Rosenkranz, Luca Brunke, Martin Offermann, Jason Herrmann, Eva Suchan, Christian Sommer, Christian Bick, and Dirk Seidensticker, special thanks go to Michael Derntl, who continuously kept track of the endless spreadsheets. Also to be mentioned is Benjamin Glissmann, who coordinated the work of the many students who tirelessly supported us.

In addition to the local support, we would like to thank a host of veteran CAA members: Guus Lange, Philip Verhagen, Steven Stead, Jeffrey Glover, Espen Uleberg, and Kai Bruhn, who provided valuable advice.

The publication could never have been produced without the help and support of Arianna Traviglia and Iza Romanowska, as well as Larissa Kurz and Till Sonnemann who brought the contributions in endless iterations of typesetting into their final form. Our sincere thanks and appreciation also go to the authors for their great patience in waiting for the final publication. We would also like to express our gratitude for the help of the University Library of Tübingen. Axel Braun helped us to set up and use the OJS portal and Sandra Binder and Susanne Schmid have been responsible for the final layout.

Editing the volume was not an easy task and was repeatedly set back by the Corona pandemic as well as by personal challenges. Therefore, we are more than happy to finally have the volume see the light of day.

Landscape Remote Sensing

CAA
2018

Clément Laplaige et al.
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Extraction of Linear Structures from LIDAR Images Using a Machine Learning Approach

Clément Laplaige
UMR 7324 CITERES-LAT
Université de Tours,
clement.laplaige@univ-tours.fr

Jean-Yves Ramel
LIFAT, Université de Tours.
jean-yves.ramel@univ-tours.fr

Xavier Rodier
UMR 7324 CITERES-LAT
Université de Tours, CNRS
xavier.rodier@univ-tours.fr

Shuo Bai
LIFAT, Université de Tours
shuo.bai@etu.univ-tours.fr

Ronan Guillaume
LIFAT, Université de Tours
ronan.guillaume@etu.univ-tours.fr

Abstract

LiDAR (Light Detection And Ranging) technology makes it possible to generate highly accurate elevation models from the ground whatever the nature of the plant cover. LiDAR elevation models have proliferated during the past decade, delivering an unprecedented number of original archaeological finds in the forest. These include habitat, agricultural or funeral structures prior to the existence of forest cover, and also archaeological micro-structures directly linked to past forest economy.

Until recently, LiDAR acquisitions in France were limited to small areas. However, the recent and rapid supply of large-scale reference data by the National Geographic Institute provides large amounts of very high-resolution data about areas covering several thousand square kilometers that were previously little known from an archaeological point of view. Manual digitization of remains is a time-consuming activity and does not guarantee exhaustive recognition of features.

As part of the "SOLiDAR" project (a tribute to the federation of unions Solidarność) (http://citeres.univ-tours.fr/spip.php?article2133), we present a Machine Learning approach enabling reliable and flexible extraction and characterization of archaeological structures discovered in the LiDAR datasets. We have developed an open human-machine interface (HMI) that is accessible to the majority of archaeologists. This system, far from being a "black box", can automatically process the remains but can also be used step by step, leaving the user to decide whether or not to validate the different processing parameters.

Keywords: LiDAR, Automated detection, Machine learning

Introduction

LiDAR technology makes it possible to generate highly accurate elevation models from the ground whatever the nature of the plant cover. It is thus possible to detect many archaeological remains related, for example, to habitat, agricultural or funeral structures.

Over and above Digital Elevation Models (DEM) or Digital Terrain Models (DTM), ground surface data obtained by Lidar surveys provide useful information about how the landscape has evolved. They can be an indirect indicator of the consequences on populations today of human activities over the long term (from earliest times to the present day).

To extract and characterize archaeological structures from LiDAR data, most studies have focused on manual identification or automatic image processing (IP). More recently, there has been an increase in the number of studies conducted on semi-automated methods based on machine learning (ML). This paper describes first the archaeological issues under-

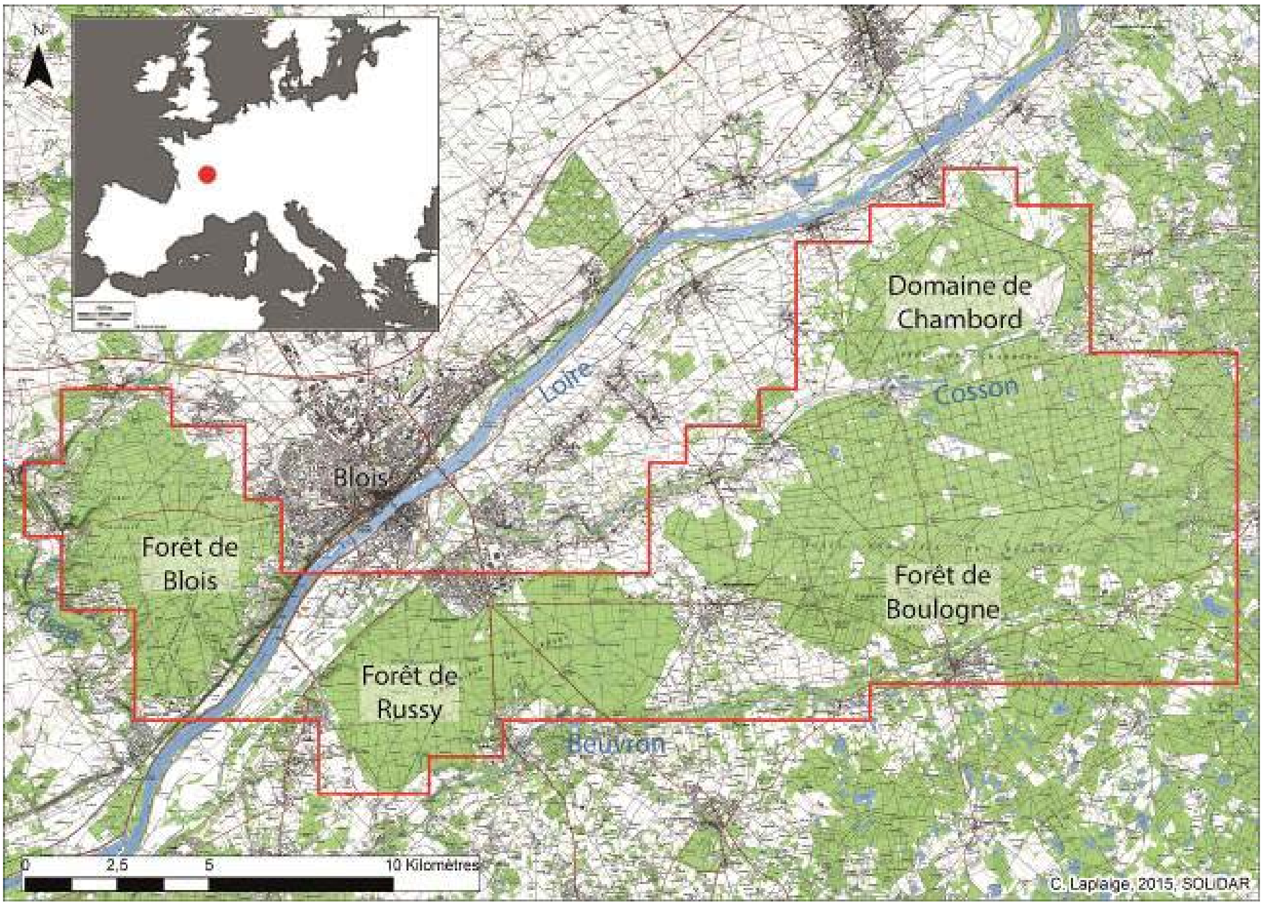

Figure 1. Boundaries of LIDAR survey and forests included in the program (C. Laplaige © SOLIDAR, IGN)

lying the SOLiDAR project and the use of conventional image processing techniques. It then presents a machine learning approach aimed at obtaining better and more flexible extraction of archaeological structures from LiDAR derivatives. The article is organized as follows: (1) the background of the work and the software that we have developed, (2) the remains investigated, (3) the data processing, and (4) the first results.

Research Context, Study Area, Data Sources and Development of Software

There are many methods for automatically processing LiDAR data; the best known is pixel analysis (Sevara et al. 2016). In the last ten years, work by geographers and computer scientists has led to more efficient methods, such as template matching and segmentation (Baatz, Hoffmann and Willhauck 2008; Blaschke 2010; Martha et al. 2010; Sevara et al. 2016).

The use of Machine Learning (Chen et al. 2014; Duro, Franklin and Dubé 2012; Li et al. 2015) has received growing attention because of the increasing availability of easy-to-use libraries and software. For example, Martha et al. used optical images for segmentation and auxiliary elevation data for landslide detection (Martha et al. 2010); Anders et al. used LiDAR DEM-derived features for geomorphological change detection (Anders, Seijmonsbergen and Bouten 2013); Eisank et al. used DEM data for drumlin delineation (Eisank, Smith and Hillier 2014); and Eeckhaut et al. used the support vector machine (SVM) algorithm and LiDAR derivatives alone for object-based mapping of landslides in forested terrain (Eeckhaut et al. 2012). SVMs, which are a generalization of linear classifiers, are a set of supervised learning techniques designed to solve discrimination and regression problems.

The use of automated recognition, especially since the advent of convolutional neural networks (CNNs), is becoming more and more widespread in the field of archaeology. Recent work has shown that

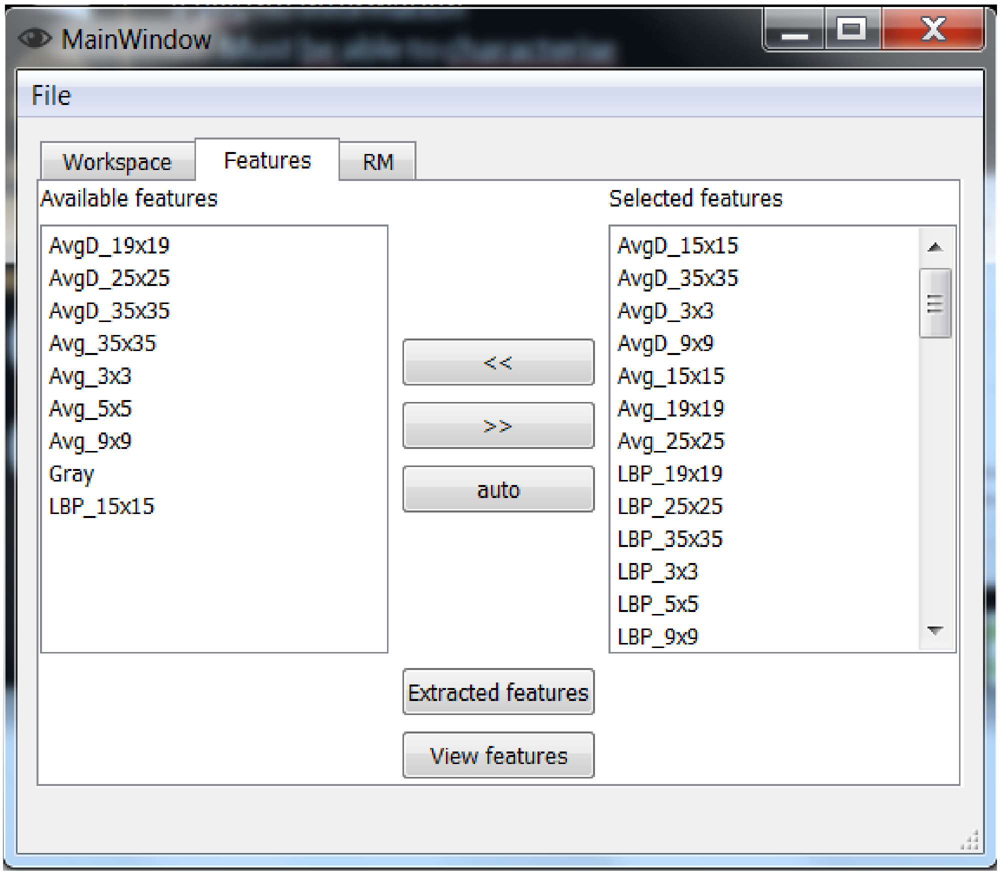

Figure 2. View of the feature selection screen of the human-machine interface (R. Guillaume, C. Laplaige)

this approach can reliably detect slopes, celtic fields, mounds and charcoal burning platforms in LiDAR datasets (Cerrillo-Cuenca 2017; Trier, Cowley and Waldeland 2019; Trier, Salberg and Pilø 2018; Trier, Zortea and Tonning 2015; Vaart and Lambers 2019).

The present work is part of the SOLiDAR project, which is included in the interdisciplinary research and innovation program entitled "Intelligence des Patrimoines". SOLiDAR brings together researchers from several fields (archaeology, history, geology, biology and data processing) and members of the Domaine National de Chambord and the French national forestry commission. It aims to establish data processing protocols aimed at understanding environmental and cultural dynamics to enable the diachronic study of land use. It combines remote sensing data and archaeological, written, geomorphological and ecological sources.

The program is based on a LiDAR survey of a 270-km^2 area around the city of Blois (Loir et Cher, France) (fig. 1), including the forests of Blois, Boulogne, Russy and the Chambord estate. In this sector, forests cover almost 25,000 ha, comprising 80% of the LiDAR acquisition area, including the Chambord estate, which was created between 1522 and 1650. The earliest mention of these forests dates back to 1176.

The LiDAR acquisition was performed at the beginning of 2015. The average density of ground points is about 10 pts / m^2, enabling DTM generation with a resolution of 50 cm. For this work, we mainly used a Topographic Position Index (TPI) (annulus, 6m – 20m) on a DTM with a resolution of 2 meters.

For this work, we developed a software application and a human-machine interface (fig. 2), meeting the following criteria:

- the system must be usable by non-specialists, i.e. it must be easy to use, and the human-machine interface (HMI) must be intuitive;
- it must be able to run on any machine and be open source;
- the system must be flexible and adaptable to different types of remains and different topographic or geomorphological conditions;

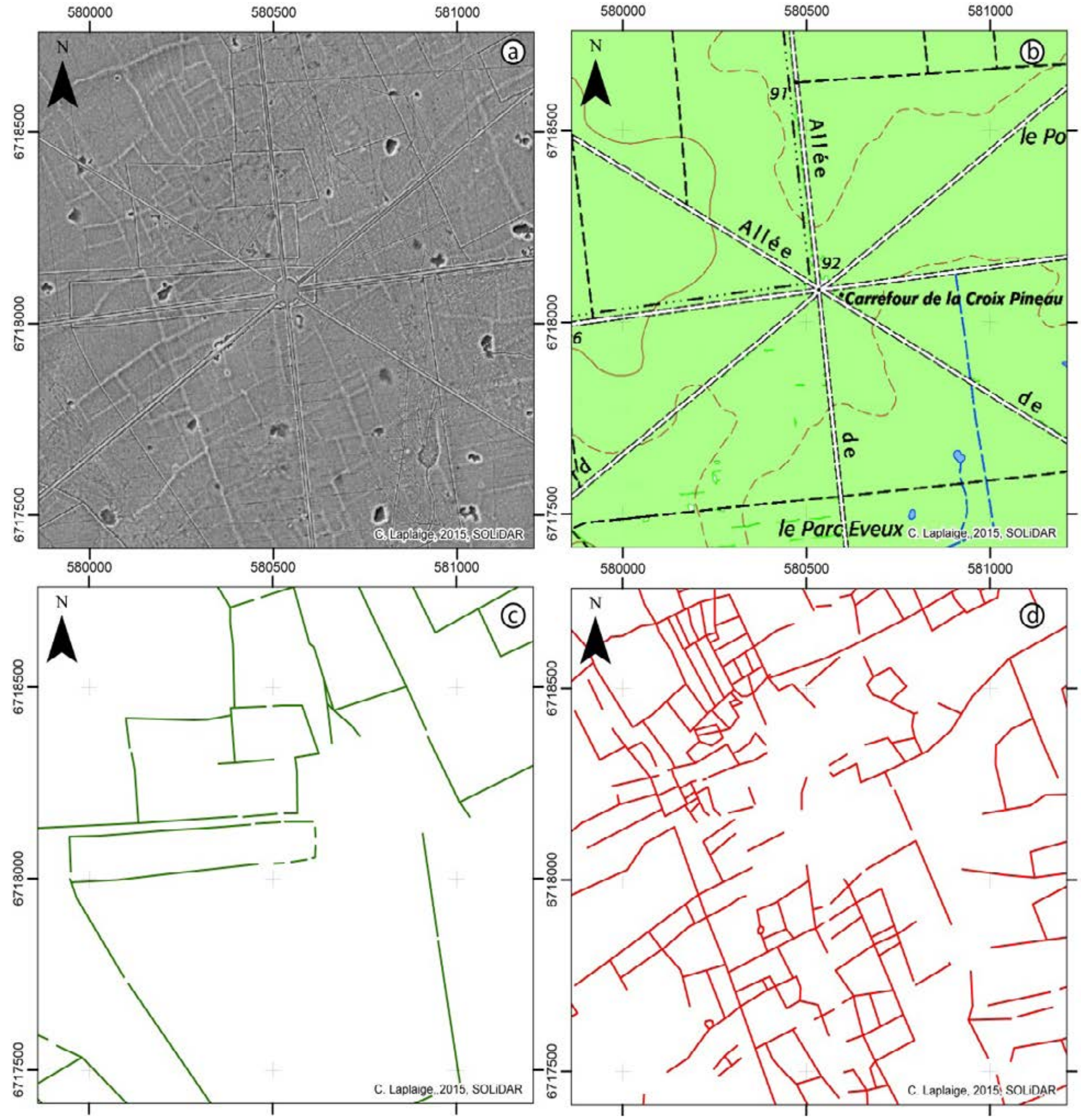

Figure 3. Vineuil, France. a) TPI revealing several micro-reliefs corresponding to archaeological remains; b) current topographic map; c) vectorization of the embankment/ditch system; d) vectorization of the embankment system (C. Laplaige © SOLIDAR, IGN)

- in order to refine archaeological interpretations, the system must provide a probability of belonging to a type of structure, rather than a presence/absence response;
- finally, the software must be able to characterize the elements that are detected.

The software was developed under Pycharm (https://www.jetbrains.com/pycharm/). It runs under version 3.5.1 of Python and uses the matplotlib 1.5.3, scikit-learn 0.18.1, scikit-image 0.12.3, numpy 1.12.0, scipy 0.19.0 and Sphinx 1.5.1 libraries.

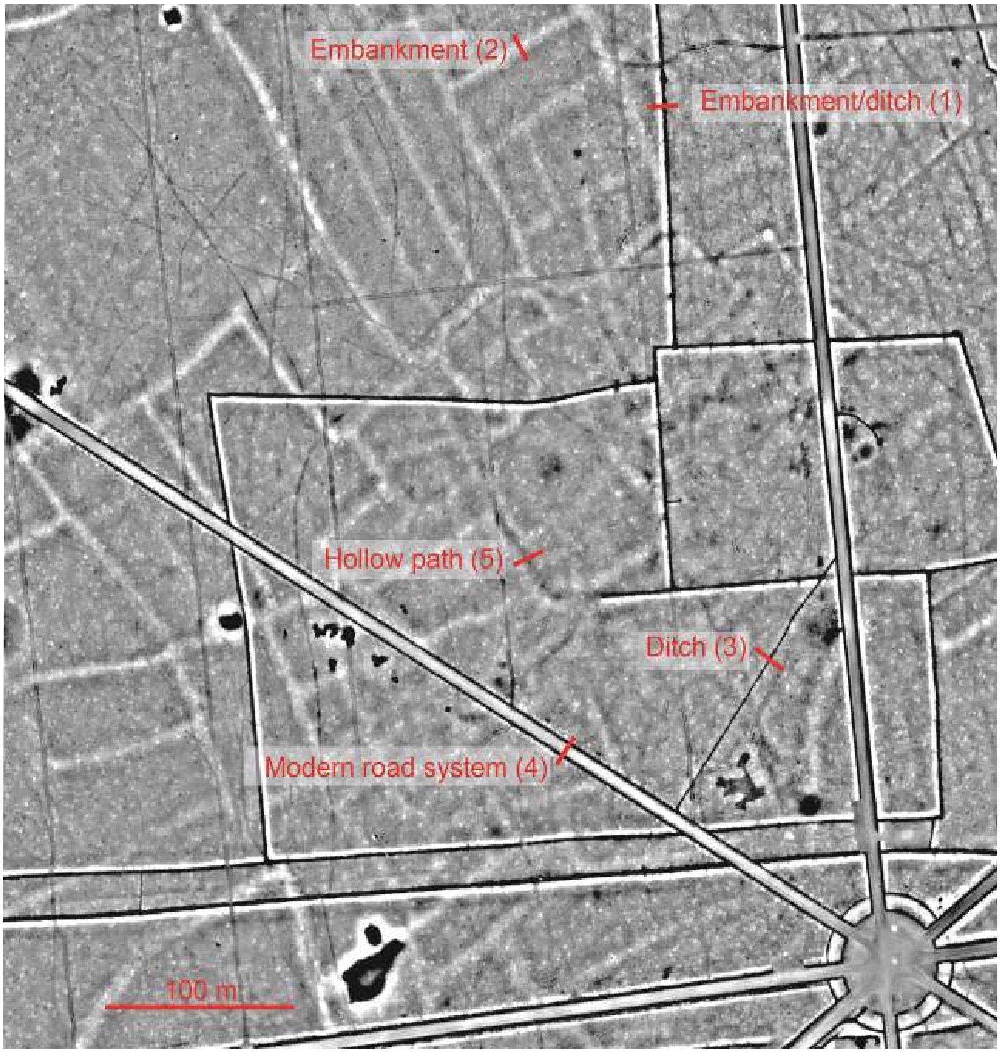

Figure 4. Elements of interest visible on a LiDAR view (C. Laplaige © SOLIDAR)

Types of Remains Investigated

We decided to focus our study on specific Elements of Interest (EOI) for archaeologists, namely linear structures. In the study area, raw LiDAR data analysis revealed at least three overlapping field system patterns (fig. 3).

On the model derived from LiDAR data, we can see in the foreground the current field system (fig. 3b), which overlaps a system of embankments and ditches consisting of rectangular, square or polygonal modules, which may or may not be embedded. In cross-section, the embankment-ditch structure is on average 6 to 8 m wide and less than one meter deep (fig. 3c). These elements were identified by field-walking prior to the LiDAR survey. The embankment-ditch system overlaps a system composed uniquely of embankments, fifteen meters wide and 10-15 cm high (fig. 4 and 5a), unknown before the LiDAR acquisition because the human eye is unable to recognize these features in the field. Some of the most impressive elements can only be seen in situ when specifically looking for them with a background LiDAR map to hand. Unlike the embankment-ditch system, which is composed of large polygonal parcels, this system is composed of tiny rectangles.

The obvious overlap between these three field systems provides an initial indication of relative chronology. The embankment system is the oldest, followed by the embankment/ditch system, and finally the current land occupation structure.

Finally, the morphological changes between these three systems suggest different uses of the space; the current system is based on hunting and forestry activities; the previous embankment/ditch system was possibly used for the same purpose, while the earlier open landscape (embankment system) was probably dedicated to agro-pastoral activities.

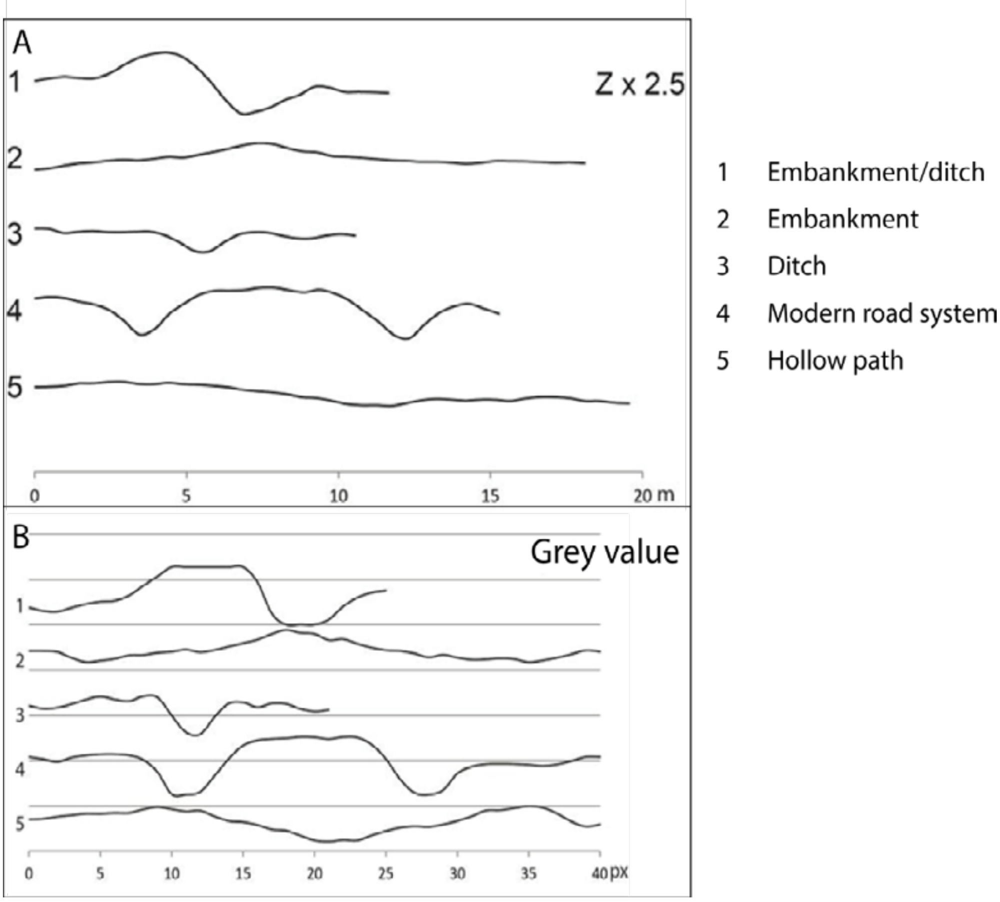

Figure 5. A. Micro-relief anomalies corresponding to features of interest (vertical exaggeration = 2.5). B. Variation of grayscale values on the Topographic Position Index corresponding to elements of interest (C. Laplaige © SOLIDAR)

Analyses of LiDAR data reveal the density of linear elements, most of which were previously undetected; more than 2,000 km have been vectorized manually. Manual digitization of these remains is a time-consuming activity and does not guarantee total recognition of features.

Until recently, LiDAR acquisitions in France were limited to small areas. However, the large-scale reference database recently produced by the French National Geographic Institute now makes vast amounts of very high-resolution data available for areas covering several thousand square kilometers that were previously little known archaeologically, opening the way for the automatic detection of features for archaeological analysis.

Selection of Elements of Interest (EOI)

The objective of the software developed by SOLiDAR is to create a system capable of detecting any type of object; however, for practical reasons and clarity of the present paper, we focus on certain linear structures (see figures 4, 5):

- Embankments/ditches (1), probably corresponding to the previous forestry system. These remains are easily detectable in elevation and in grayscale. In both cases, a steep slope can be observed followed by a depression.

- Embankments (2), corresponding to the earlier system and related to agricultural activities. While not easily discernible in the topography, TPI enables them to be observed in grayscale.

- Ditches (3), with drainage functions. They are easily recognizable by the simple depression.

- Modern road system (4), composed of two ditches, one on either side of a central line of solid ground.

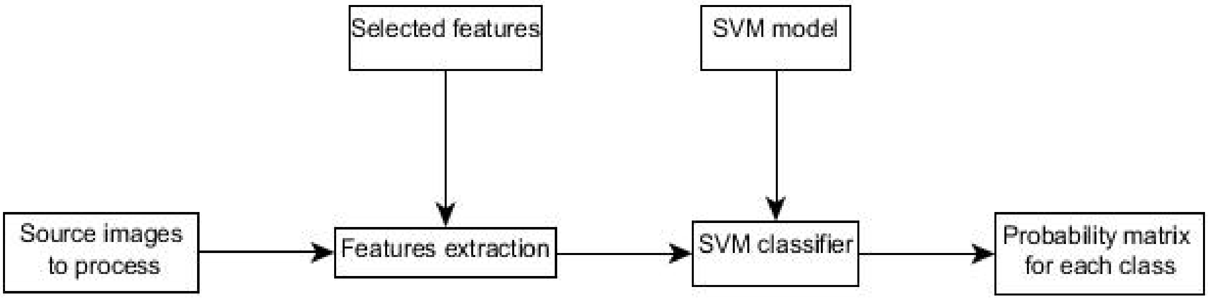

Figure 6. Vineuil, France. a) TPI revealing several micro-reliefs corresponding to archaeological remains; b) current topographic map; c) vectorization of the embankment/ditch system; d) vectorization of the embankment system (C. Laplaige © SOLIDAR, IGN)

Name of element	ditch/ Embankment (1)	Embankment (2)	Ditch (3)	modern	ancient	other	TOTAL
Number	21611	53739	5994	23322	9236	22792	136694

Table I: Summary of the number of pixels integrated in ML processing (S. Bai)

- Probable hollow-way (5). This element is very difficult to recognize in the topography, where it corresponds to a very shallow depression.

Machine Learning Framework

First, we used a conventional image-processing approach to identify the previously defined elements. The goal was to separate the pixels of an initial image into the 5 targeted information layers. Different processing sequences were tested, including: image filtering (median /Gaussian, etc.), multiple thresholding, mathematical morphology operations, connected component analysis, and arithmetic operations between processed DEM and layers. Finally, we examined semi-automated methods based on Machine Learning to create a more flexible and robust framework to characterize archaeological structures from LiDAR derivatives (fig. 6).

Training Step

Selection and Organization of the Training Dataset

The first step involves selecting the input images (DEM) that will be used to compute the pixel features. Based on the expertise of archaeologists and on the results obtained with IP methods, we computed the features using only the Topographic Position Index proposed by Jeff Jenness with a resolution of 2m (Jenness, Brost and Beier 2013). One of our goals is to extract information from other types of visualization (e.g. slope or positive aperture), but this has not yet been achieved.

In the HMI, all that is needed is to define the elements to be detected, and the system creates and organizes the folders. Thereafter, it is necessary to copy the original image and absence/presence images for each element.

For this article, we selected 20 8-bit LiDAR images. For each image, we created 5 binary images (one per class) (fig. 7). The whole set (8-bit image plus the binary images) is used to train the system. We tried to include as many elements as possible and balance the number of pixels for each one (Table I).

Selection of the Features for Pixel Classification

When designing a classification system, the selection of the features to describe the pixels is vital, as well as the content of the training dataset, because they determine the quality of the classification results. We drew up a list of features based on our experience in computer vision. These features are inspired by the well-known and efficient LBP

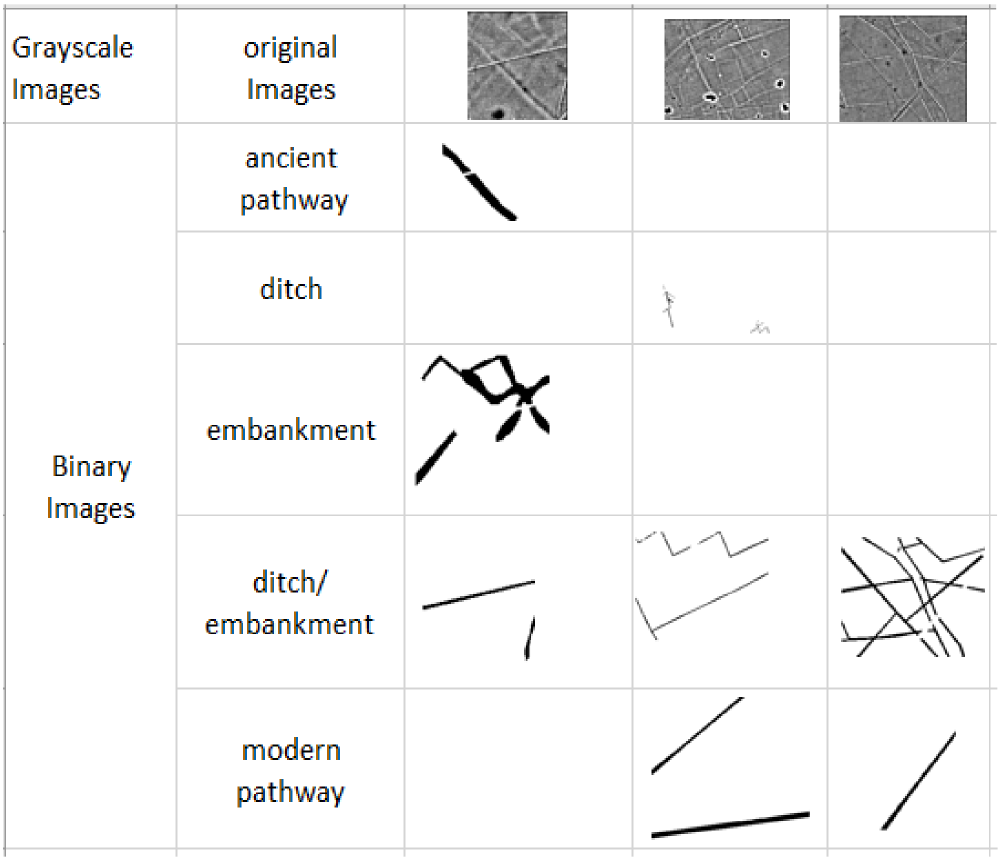

Figure 7. 8-bit TPI extracts and corresponding binary images for each element (S. Bai)

(local binary pattern) method (Ojala, Pietikäinen and Harwood 1996) in which the grayscale values of the local neighborhood are thresholded against the central pixel to provide a binary pattern called texture unit. The number of occurrences of each texture unit is used as descriptors of a region inside an image. We propose an adaptation of this idea to compute the features included in our framework by considering a local neighborhood (of variable mask size) around a central pixel. The features are computed using statistics about grayscale values in different neighborhoods and comparing those values with the value of the central pixel. Currently, the system includes 64 features of 9 types. We think that it should be left to each operator to decide whether to select a feature manually or automatically. In the latter case, features can be selected using a Sequential Forward Floating Selection Method (SFSM) (Pudil, Novovičová and Kittler 1994), which enables different features to be added and subtracted in order to obtain the best possible recognition rate. This rate is calculated by comparing the binary images provided to the system with the detection proposals of the classification algorithm.

Construction of the Classification Model

For the classification, different machine learning algorithms can be adopted and plugged into our framework. For the moment, we have incorporated an SVM classifier in the system. SVM is a non-parametric kernel-based technique based on statistical learning theory, optimization of algorithms, and structural risk minimization theory, and it has been used in many studies. SVM parameters can be optimized using an N-fold cross-validation grid search function.

In this study, since the classes are not linearly separable, a radial basis function (RBF) kernel was used to implement the classification in a higher dimension space. The cost and gamma parameters can be determined by cross-validation.

Once the kernel and major parameters have been set, the SVM model for classification is constructed.

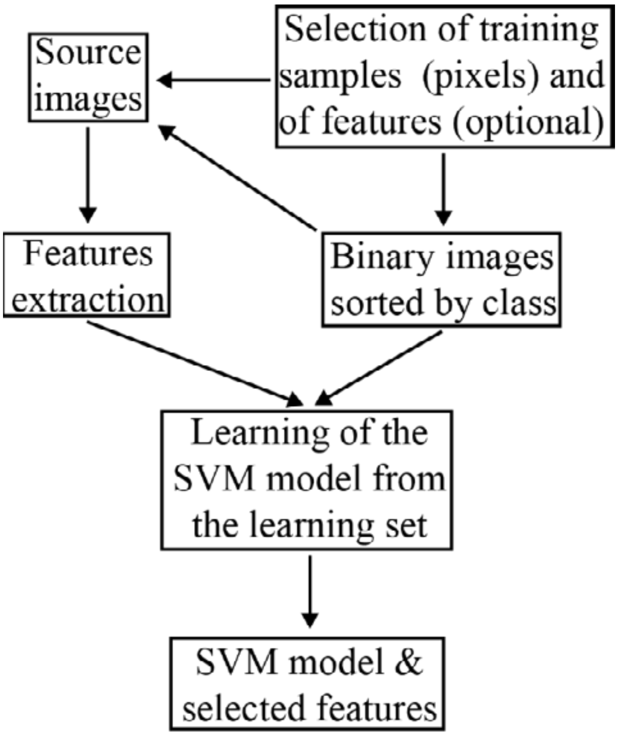

Figure 8. Schematic representation of the SVM Classifier framework (S. Bai, C. Laplaige)

Classification Step

To classify a new image, the first step is to calculate the features of each pixel. The features to use here should be the same as those chosen in step 4.1.2 used to build the SVM model. Those pixels with features are then sent to the SVM model, and the SVM model will calculate the probability of each pixel belonging to each element.

After classification, six probabilities are generated for each pixel, corresponding to 6 classes (5 classes of remains + 1 class of everything else). Probability maps corresponding to all the desired classes of Elements of Interest have to be combined to provide the final decision. Different fusion techniques can be used during this step. In this first study, we used a maximum rule with reject option for the combination and each pixel is assigned to the class with the maximum probability only if the value is higher than a predefined, empirically chosen threshold.

Next, the binary image obtained can be vectorized in a similar way as binary images obtained with a conventional image-processing sequence. This function has not yet been implemented, but we hope to use systems such as those described by Ramel et al. for that purpose (Ramel, Vincent and Emptoz 2000).

First Results

Evaluation Protocols

The position match (PM) was selected to evaluate the EOI inventory map obtained. PM is defined as:

$$PM = \frac{A_{R \cap O}}{A_{R \cup O}} \times 100\%$$

where $A_{R \cup O}$ is the area designated as an EOI either in the reference inventory or in the results, and $A_{R \cap O}$ is the area designated as an EOI in both the reference inventory and in the results, namely, the union (∪) and intersection (∩) of two inventory maps.

A high PM value demonstrates that the two inventories are essentially similar with a good quality of results.

Qualitative Results

An example of processing performed by the SVM is shown in figure 9. On the left, we can see an embankment system, and on the right, the probability of each pixel being an embankment (black corresponds to a 100% probability). We can see that the greatest probability is for the largest remains; the detection of smaller features is less evident. The analysis of this kind of image helps understand the SVM process and improve the system.

Quantitative Results

For this first test, 30,000 samples were used to generate the learning base of SVM, with approximately the same number for each element. The results (PM value %) are displayed in the confusion matrix below (Table II).

The percentage corresponds to remains detected in each class of elements. For example, if we look at the second line, 2% of embankments are detected as other, 50% as embankments, 6% as ditches, etc. For the moment, the error rate is close to 60%. We can see that this is the class with the poorest results, as ancient pathways are particularly difficult to detect,

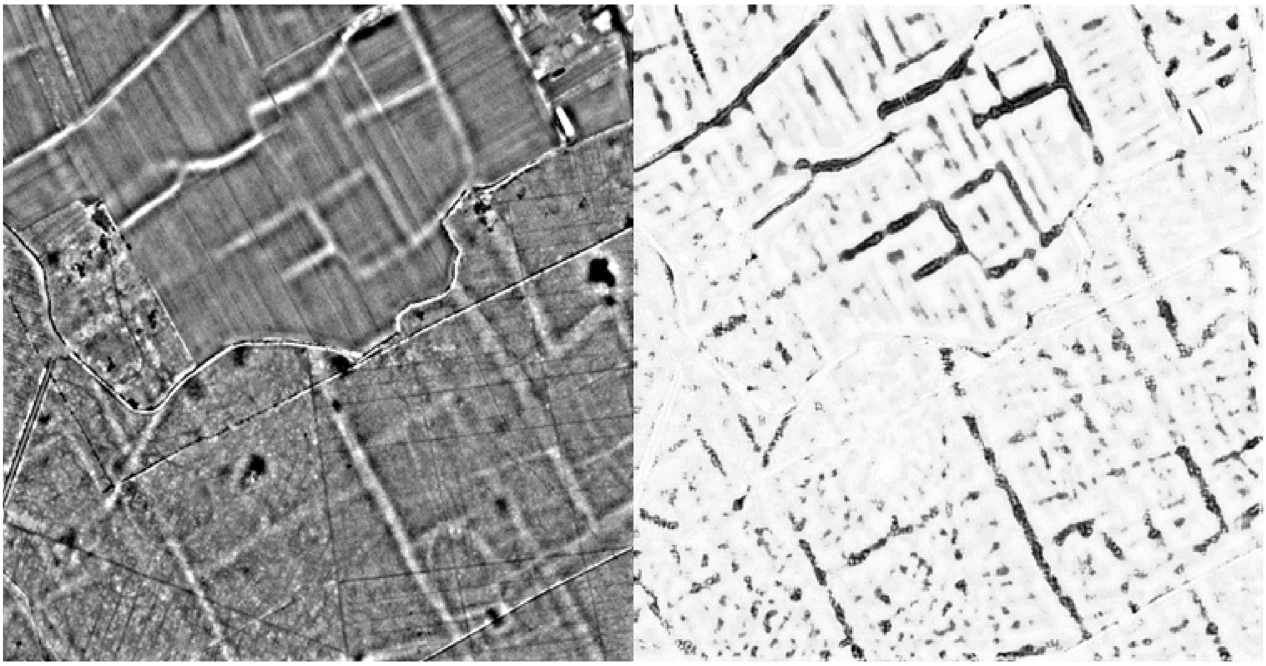

Figure 9. On the left: TPI of an area near Blois. On the right: representation of the probability for each pixel being an embankment (black = 100%, white = 0%) (C. Laplaige)SOLIDAR, IGN)

	Ditch/ embankment (1)	Embankment (2)	Ditch (3)	Modern pathway (4)	Ancient pathway (5)	Other
Ditch/ embankment (1)	40	9	12	22	10	8
Embankment (2)	2	50	6	1	18	23
Ditch (3)	29	1	38	27	4	1
Modern pathway (4)	29	5	5	41	12	6
Ancient pathway (5)	3	35	7	3	28	23
Other	4		6	2	17	31

Table II: Position match value for each element (S. Bai)

	Recall	Precision	F1	MaF1
Ditch/ embankment (1)	0.4	0.37	0.39	
Embankment (2)	0.5	0.36	0.42	
Ditch (3)	0.38	0.45	0.41	0.39
Modern pathway (4)	0.41	0.43	0.42	
Ancient pathway (5)	0.28	0.31	0.29	

Table III: Results of the test

even by an expert. We have not yet found the right features to clearly describe these elements.

We can also see some confusion between modern pathways and embankments/ditches, and between ditches and modern pathways and the embankment/ditch system. It is difficult to differentiate composite structures using only selected features. In addition to testing new features and looking at vectorization processes to increase the detection rate, it would be interesting to work with fewer types of structures.

We decided to test the ability of this system to classify several types of remains simultaneously (table III). The recall and precision values are between 0.3 and 0.5. The F1 score, which measures the model's performance, has values around 0.4. If we look at the error rate as a whole, it appears that it is higher than the rates reported in other studies (error rate is close to 60%.), for example, for the detection of mounds (Freeland et al. 2016; Sevara et al. 2016). However, the desire to deal with linear rather than isolated objects and to attempt to classify different elements simultaneously effectively limits the overall quality of recognition of the remains.

Conclusion and Outlook

This work is a first attempt to develop a generic Machine Learning framework for the semi-automatic extraction of archaeological elements based on LiDAR DEM. We have created an open-source software application usable by non-specialists. This system, which can be used semi-automatically or manually, can be adapted to different types of remains and to different topographical constraints. The work is in its initial stages, focusing on the extraction of linear structures. It rapidly became clear that the Machine Learning approach has considerable advantages over image processing techniques.

The software has started to be distributed at seminars and will be available for download this summer. The first feedback allowed us to observe a good compatibility of the software on various operating systems and computers. In addition, users with little training in the use of machine learning appreciated the ease of use.

The generation of probabilities rather than binary images from the extraction should allow new databases to be created that can be equally well interpreted. The main idea of this approach is to find a neat way to combine information derived from the DEM (LIDAR data) in order to see whether each pixel is part of a specific Element of Interest. The output of this new framework will be a set of matrices called "probability maps". Each probability map includes the probabilities for each pixel of the image to be part of a specific EOI.

The system is now stable and portable on any type of machine without prior installation, and we can now focus on improving system performance, notably to increase the detection rate. To this end, we are working on several aspects. We wish to add new features and work on several types of LiDAR data visualization. We are looking at the possibility and interest of adding a convolutional neural network to use with our data sets.

Finally, this paper presents only one module of a tool composed of two parts. This module allows you to locate elements of interest freely defined by users in LIDAR data. The output of this module is probability maps of the presence of these elements at the pixel level.

The second module, designed to transform probability maps into vectorized structures (Ramel, Vincent and Emptoz 2000), is currently under development.

References

Anders, N S, Seijmonsbergen, A C and Bouten, W 2013 Geomorphological Change Detection Using Object-Based Feature Extraction From Multi-Temporal LiDAR Data, *IEEE Geoscience and Remote Sensing Letters*, 10(6): 1587–1591. DOI: https://doi.org/10.1109/LGRS.2013.2262317

Baatz, M, Hoffmann, C and Willhauck, G 2008 Progressing from object-based to object-oriented image analysis. In: Blaschke, T, Lang, S, and Hay, G J (eds.) *Object-Based Image Analysis*. Lecture Notes in Geoinformation and Cartography. Springer Berlin Heidelberg. pp. 29–42. DOI: https://doi.org/10.1007/978-3-540-77058-9_2

Blaschke, T 2010 Object based image analysis for remote sensing, *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(1): 2–16. DOI: https://doi.org/10.1016/j.isprsjprs.2009.06.004

Cerrillo-Cuenca, E 2017 An approach to the automatic surveying of prehistoric barrows through LiDAR, *Quaternary International*, 435: 135–145. DOI: https://doi.org/10.1016/j.quaint.2015.12.099

Chen, W, Li, X, Wang, Y, Chen, G and Liu, S 2014 Forested landslide detection using LiDAR data and the random forest algorithm: A case study of the Three Gorges, China, *Remote Sensing of Environment*, 152: 291–301. DOI: https://doi.org/10.1016/j.rse.2014.07.004

Duro, D C, Franklin, S E and Dubé, M G 2012 A comparison of pixel-based and object-based image analysis with selected machine learning algorithms for the classification of agricultural landscapes using SPOT-5 HRG imagery, *Remote Sensing of Environment*, 118: 259–272. DOI: https://doi.org/10.1016/j.rse.2011.11.020

Eisank, C, Smith, M and Hillier, J 2014 Assessment of multiresolution segmentation for delimiting drumlins in digital elevation models, *Geomorphology*, 214: 452–464. DOI: https://doi.org/10.1016/j.geomorph.2014.02.028

Freeland, T, Heung, B, Burley, D V, Clark, G and Knudby, A 2016 Automated feature extraction for prospection and analysis of monumental earthworks from aerial LiDAR in the Kingdom of Tonga, *Journal of Archaeological Science*, 69: 64–74. DOI: https://doi.org/10.1016/j.jas.2016.04.011

Jenness, J, Brost, B and Beier, P 2013 *Land Facet Corridor Designer: Extension for ArcGIS*. Jenness Enterprises.

Li, X, Cheng, X, Chen, W, Chen, G and Liu, S 2015 Identification of Forested Landslides Using LiDar Data, Object-based Image Analysis, and Machine Learning Algorithms, *Remote Sensing*, 7(8): 9705–9726. DOI: https://doi.org/10.3390/rs70809705

Martha, T R, Kerle, N, Jetten, V, van Westen, C J and Kumar, K V 2010 Characterising spectral, spatial and morphometric properties of landslides for semi-automatic detection using object-oriented methods, *Geomorphology*, 116(1): 24–36. DOI: https://doi.org/10.1016/j.geomorph.2009.10.004

Ojala, T, Pietikäinen, M and Harwood, D 1996 A comparative study of texture measures with classification based on featured distributions, *Pattern Recognition*, 29(1): 51–59. DOI: https://doi.org/10.1016/0031-3203(95)00067-4.

Pudil, P, Novovičová, J and Kittler, J 1994 Floating search methods in feature selection, *Pattern Recognition Letters*, 15(11): 1119–1125. DOI: https://doi.org/10.1016/0167-8655(94)90127-9.

Ramel, J Y, Vincent, N and Emptoz, H 2000 A structural representation for understanding line-drawing images, *International Journal on Document Analysis and Recognition*, 3(2): 58–66. DOI: https://doi.org/10.1007/s100320000037

Sevara, C, Pregesbauer, M, Doneus, M, Verhoeven, G and Trinks, I 2016 Pixel versus object — A comparison of strategies for the semi-automated mapping of archaeological features using airborne laser scanning data, *Journal of Archaeological Science: Reports*, 5: 485–498. DOI: https://doi.org/10.1016/j.jasrep.2015.12.023

Trier, Ø D, Cowley, D C and Waldeland, A U 2019 Using deep neural networks on airborne laser scanning data: Results from a case study of semi-automatic mapping of archaeological topography on Arran, Scotland, *Archaeological Prospection*, 26(2): . DOI: https://doi.org/10.1002/arp.1731

Trier, Ø D, Salberg, A-D and Pilø, L H 2018 Semi-automatic mapping of charcoal kilns from airborne laser scanning data using deep learning. In: *Oceans of Data. Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology*. Archaeopress. Oxford: Matsumoto, M and Uleberg, E. pp. 219–231.

Trier, Ø D, Zortea, M and Tonning, C 2015 Automatic detection of mound structures in airborne laser scanning data, *Journal of Archaeological Science: Reports*, 2: 69–79. DOI: https://doi.org/10.1016/j.jasrep.2015.01.005

Vaart, W B van der and Lambers, K 2019 Learning to Look at LiDAR: The Use of R-CNN in the Automated Detection of Archaeological Objects in LiDAR Data from the Netherlands, *Journal of Computer Applications in Archaeology*, 2(1): 31–40. DOI: https://doi.org/10.5334/jcaa.32

Eeckhaut, M van Den, Kerle, N, Poesen, J and Hervás, J 2012 Object-oriented identification of forested landslides with derivatives of single pulse LiDAR data, *Geomorphology*, 173: 30–42. DOI: https://doi.org/10.1016/j.geomorph.2012.05.024

URL

SOLiDAR: http://citeres.univ-tours.fr/spip.php?article2133
Intelligence des patrimoines: https://www.intelligencedespatrimoines.fr
Topographic Position Index: http://www.jennessent.com

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Multispectral Images Classification Applied to the Identification of Archaeological Remains: a Post-Dictive Perspective

Andrea Gennaro
Mibac, SABAP Reggio
andreamaria.gennaro@cultura.gov.it

Giuseppe Mussumeci
Dept. of Civil Eng. and Arch., L'Università di Catania
g.mussumeci@dica.unict.it

Michele Mangiameli
Dept. of Civil Eng. and Arch., L'Università di Catania
michele.mangiameli@dica.unict.it

Alessio Candiano
Dept. of Civil Eng. and Arch., L'Università di Catania
ale.candiano90@gmail.com

Gabriele Fargione
Dept. of Civil Eng. and Arch., L'Università di Catania
gabriele.fargione@gmail.com

Abstract

Automated and semi-automated image classifications have made their way into archaeological applications, but early attempts have been strongly criticized. This study examines semi-automated detection methods of archaeological evidence through a comparison of pixel-based and object-oriented data classification. This research has been carried out on high-resolution imagery (WorldView-2) and the selected case study is located on the western slope of Etna (Sicily), the highest volcano in Europe, where a huge variety of settlements can be found from Prehistoric to Medieval times. The methodology of both pixel-based and object-based data classification is described and discussed over to specific case-study. The different nature of the two methods combined with the post-dictive approach adopted provides useful results in order to determine robustness and weakness of techniques presented here. In fact, our goal is to analyze advantages and disadvantages of the usage of pixel and object-based classification techniques and shed light on the significant change in pattern recognition. Finally, the obtained data are compared with manual visual interpretations and analyzed in terms of their accuracy.

Keywords: pixel-based classification, OBIA, volcanic environment

Introduction

In the last years, the archeological community is starting to take account of the advantages in employing computer-aided analysis techniques, which can help in classifying large area rapidly and high-resolution archaeological data. The starting point of this revolution is clear: it's a fact that we now have the capability to produce so much data of such high spatial, spectral and temporal quality that it is becoming extremely difficult to process and interpret it all manually. Consequently, the data explosion has generated new challenges and new scenarios. While in fields such as environmental remote sensing, medical imaging, security and robotics automated and semi-automated techniques are routine, they are still in its infancy in archaeology (Bennett, Cowley and De Laet 2014). The benefits and the limitations to which such approaches are applicable continue to be debated, and it seems there's certain reluctance in archaeology to accept the notion of computer-aided features detection. Interpretation of archaeological features is clearly heavily conditioned –in a positive and negative way- by the abilities and the experience of the interpreter. Algorithms will never replace the skills of an archaeologist but, at the same time, multiple interpretations are often ineluctable. The critical issue is embedded in the exact definition of what can be considered as "archaeological feature".

From this perspective, instead of declining the notion of computer-aided detection of archaeological information, the goal should be finding general procedures and work-flows in which we can use these techniques in archaeology (Calderone et al. 2022; Mangiameli et al. 2020; Gennaro et al. 2018). Automated and manual processes should not be evaluated as alternatives and separate methods but rather as complementary wheels of a holistic approach.

In this paper, we are going to discuss two different approaches to semi-automated features extraction of information that are frequently used nowadays in the fields of archaeology and image-analysis: pixel-based and object-oriented classifications. In particular, we evaluate the applicability of these methods for the identification of archaeological features in the western slope of Etna (Gangi et al. 2020), the European highest volcano, using a multispectral dataset (Candiano et al. 2019; Mangiameli, Mussumeci & Candiano 2018) and adopting a post-dictive approach (Gennaro et al. 2019 b). Therefore, the first part is dedicated to the geographic and archaeological context, while in the second, softwares are applied to obtain pixel-based and object oriented classification. The results demonstrate that photo interpretation and mapping can be performed much more effectively based on object-based classification.

The Archaeological Context

The selected case study is of great archaeological interest and it lies on the Western slope of the European highest active volcano, Etna (Figure 1). The mountain and its spectacular activity are rooted in the collective imagination and memory of modern and ancient inhabitants. So, it is not surprising that Etna has been the protagonist of numerous myths and legend since ancient times. According to Homer, for example, the forge of the god Ephestus was located in the volcano's bowels; Empedocles, the famous pre-Socratic rationalist, left his hometown, Agrigento, and died, throwing himself into the volcano, while he was studying the nature of fire and magma. Even Catania's patron saint, Saint Agata, is linked to Etna. Indeed, it is believed that, during a destructive eruption in 1169, the lava flow was miraculously stopped by the saint's veil and so the city of Catania was saved (Guidoboni et al. 2014). Mount Etna has been inscribed in the UNESCO World Heritage List in June 2013. It is worth mentioning that the scientific committee describes «*Mount Etna (as) one of the best-studied and monitored volcanoes in the world, and continues to influence volcanology, geophysics and other earth science disciplines. Mount Etna's notoriety, scientific importance, and cultural and educational value are of global significance* ».

Despite the human presence in the North-West side of Etna goes back to the Neolithic Age (Privitera, 1998; Spigo, 1985), unfortunately archaeological interest has never been strong (Orsi 1905; Orsi 1907). The prehistoric cave occupation is the only evidence that archaeologists have extensively studied for many years (Privitera, 2007). The western flank is much less studied than the southern and eastern ones. Our investigated zone lies between three districts, Balze Soprane, Santa Venera and, mainly, Edera; a national roadway (S.S. 120) constitutes the northern limit and the total extent of the sample area is around 1,3 sq.km. This portion of territory, located above 800-900 m a. s. l, is part of a large and characteristic lava plain of the Saracena's valley, a tributary of the Simeto river, in the territory of Bronte. Thanks to its great naturalistic interest from a geologic, floristic-vegetation and faunal point of view, the entire area, belonging to Etna Park, has been identified by European Union as a Site of Community Importance (SCI). The final result is an extraordinary and unique landscape. From an archaeological point of view, the geomorphological elements mentioned above represent some of the main problems encountered in the landscape analysis. In addition, all the ancient buildings are made of lava stone blocks and this produces another obstacle for the archaeological interpretation. In the Edera district systematic excavations undertaken by the Soprintendenza of Catania completely brought to light a dozen of circular and rectangular buildings (Puglisi & Turco 2015) (Figure 2). Most of them, dated to Byzantine era (VIII-IX century) are located in the

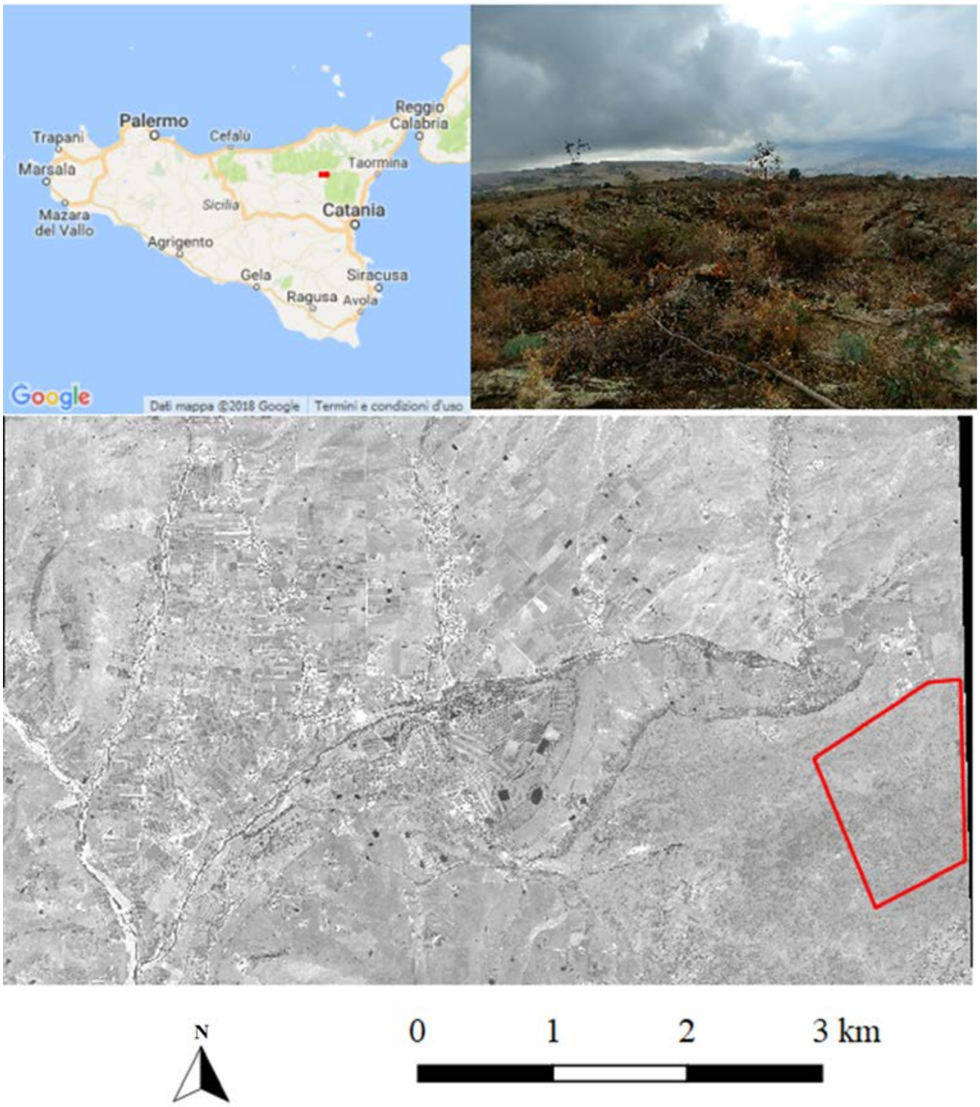

Figure 1. Location map of the study area.

southern edge of the district, not so far from the national road, and they are known as Building 1, Building 2 and so on; the remaining part, built in Greek times, has been discovered near the modern Masseria (farm) Edera. In addition, wall-structure runs across the districts for about 2 km (Figurer 3). Unfortunately, it is not easily framed chronologically and it's still today object of studies. However, some scholars have interpreted the structure as a Byzantine fortification wall dated to Early medieval times (Leone et al. 2007).

Dataset

The WorldView-2 satellite sensor provides panchromatic and multispectral data with geometric resolutions of 0.46-0.52 m and 1.85–2.07 m, respectively, depending upon the off-nadir viewing angle (0 to 20°). The panchromatic sensor collects information at the visible and near-infrared (NIR) wavelengths. The multispectral sensor acquires data in 8 spectral bands from coastal to NIR-2. Both panchromatic and multispectral sensors offer 11bits (2048 gray levels) resolution. The WorldView-2 imagery products are available at different processing levels (basic, standard, orthorectified) serving the needs of different users. The WorldView-2 data used for this study were acquired on April 19, 2013. In this research, the pansharpening was performed using Orfeo Toolbox in QGIS. The application of this algorithm allowed a noticeable improvement of the image quality in terms of spatial resolution. In particular, starting from the 8-band multispectral image with GSD equal to 2 m, we obtained the analogous multispectral image having GSD equal to 0.50 m.

Figure 2. Archaeological structures already excavated in Edera district (from Puglisi & Turco 2015)

Tools and Classification Techniques

The entire study was conducted using, mainly, free and open source software (FOSS) within a low-cost logic that allows study of landscapes using limited budgets. In particular, the processing of the acquired data was performed with QGIS and its plugins. QGIS is a GIS free software and open source that has potential similar to equivalent commercial GIS and it is possible to extend functionality via native or external plugins. In particular the Semi-Automatic Classification Plugin (SCP) was used, which is a FOSS plugin that allows to process multispectral images and to perform their supervised classification. Furthermore, ever within the QGIS platform, the tools of Orfeo Toolbox were used. OTB is an open-source C ++ library for processing remote sensing images that includes several feature extraction, filtering, classification and segmentation algorithms. Regarding eCognition, this is the widely used commercial software for OBIA solutions. It is used in earth science to develop rule sets for the automatic analysis of remote sensing data. Besides, the extracted features can be exported in raster or vector format allowing integration into GIS applications. This software has been already applied in archaeology for feature recognition. As mentioned above, we used SCP for the pixel-based classification and eCognition (trial version) for the object-based analysis.

Classification techniques can be distinguished into the following two main broad categories:

- Pixel-based techniques or PBIA (acronym for Pixel Based Image Analysis), based exclusively on the spectral information contained in the individual pixels in the image.

Figure 3. The wall-structure (photo by authors)

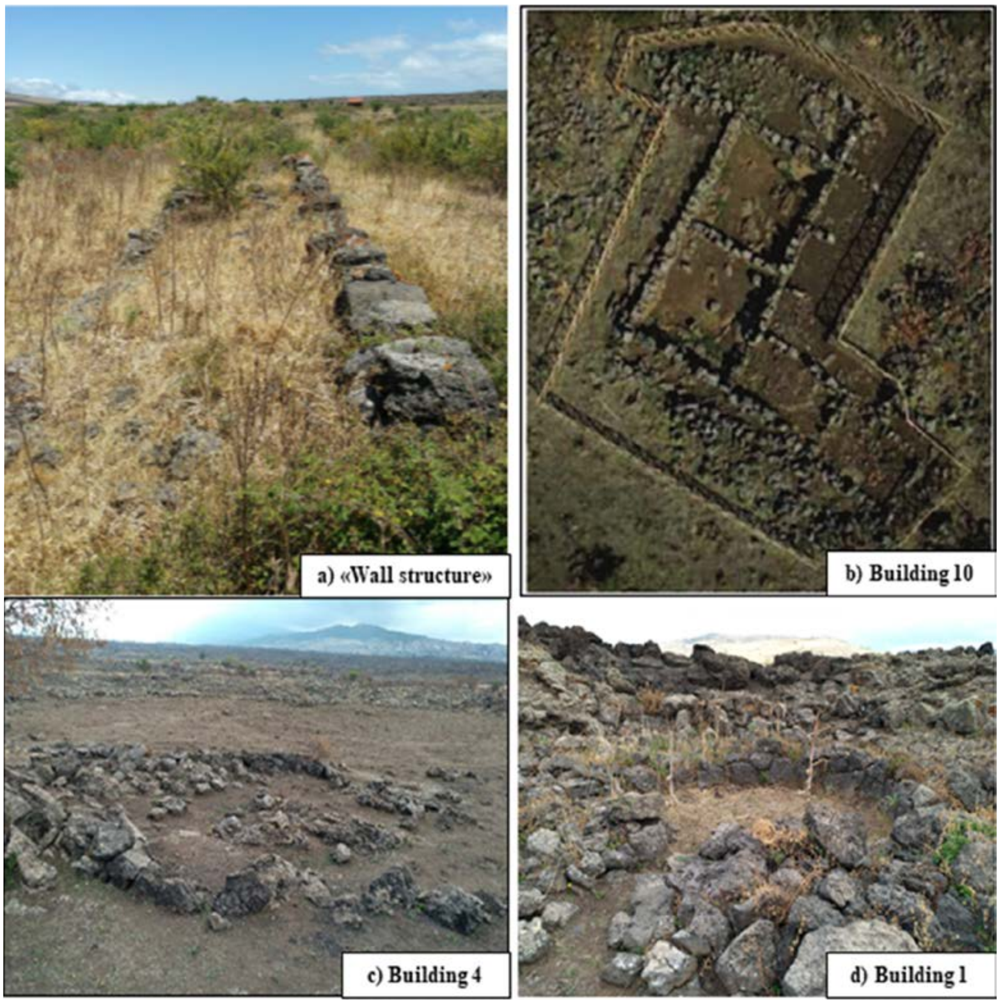

Figure 4. RMacro-class of rock divided in 4 sub-classes.

- Object-based or OBIA techniques (acronym for Object Based Image Analysis), which use information related to groups of pixels, considering the interrelations between adjacent pixels.

In the archaeological field, the classification procedures used have traditionally been pixel-based (De Laet, Paulissen, & Waelkens, 2007; D'Orazio, Palumbo, & Guaragnell 2012; Schuetter et al. 2013; Lasaponara et al. 2014); in recent years, scholars are moving towards the use of object-based techniques in order to obtain thematic maps characterized by a greater information content (Lasaponara et al. 2016; Sevara et al. 2016).

The detection of archaeological features, especially buried evidence, is a really complex task and modern techniques may be not so effective (Parcak 2009). Traces of archaeological remains include different features, which cannot be characterized by any specific color or tone of gray in the image, but rather by their huge heterogeneity. Archaeological marks (as crop, soil, shadow) might be easy to extract in a visual photo-interpretation process, but heir heterogeneity makes their automatic or semi-automatic classification problematic.

Pixel Based Classification

Pixel-based methodology uses the smallest entity within an image, the picture element (or pixel), in order to extract the feature information in relation to one or more predefined classes.

Therefore, the classification algorithms operate on individual pixels by analyzing the radiometric information, i.e. the value of the digital number (DN), of every single pixel present in the image. The assignment of the pixels to the classes takes place at the level of the single pixel and depends exclusively on its spectral content. The classes have either

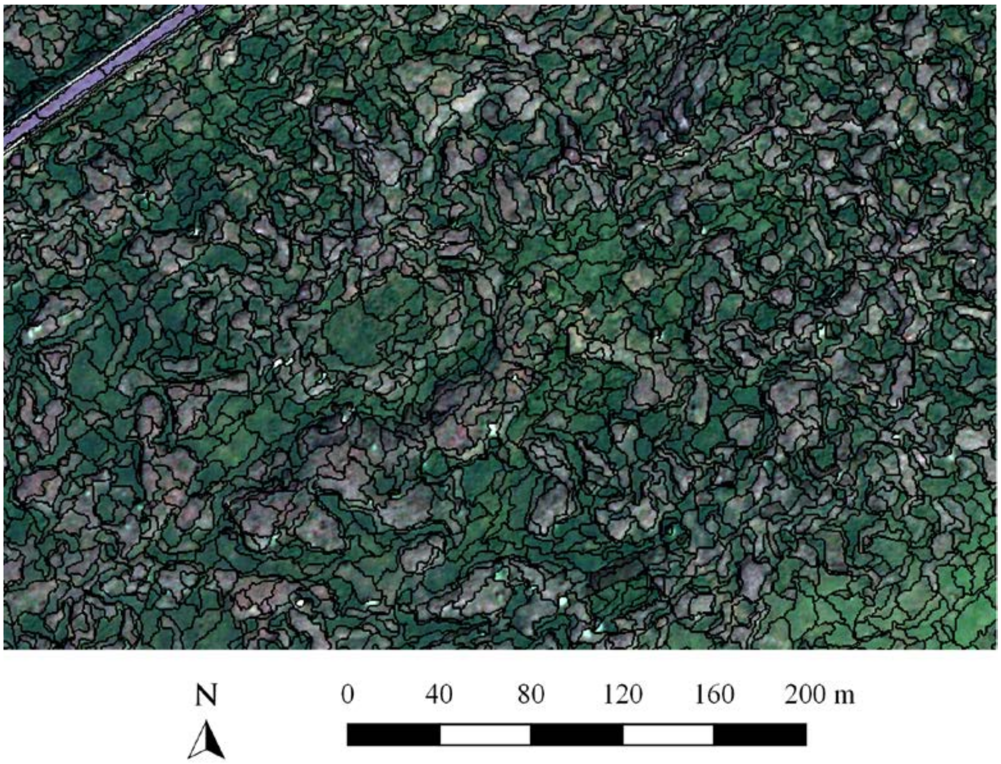

Figure 5. Segmentation process's results.

been predefined by the investigator in the form of a supervised classification approach, or identified by the software in an unsupervised approach based on grouping the spectral properties of the multispectral image's pixel.

Only the supervised pixel-based approach seems to be successful for archaeological feature detection, which first requires the definition of the number and nature of the classes to be represented in the thematic map. In the first phase (training), it is necessary to identify the thematic classes that will be extracted and represented in the classification. Moreover, the so-called training area or Region Of Interest (ROI) have to be identified in order to build a "model" of the thematic class, which consists in the creation of a characteristic and distinctive spectral signature of the considered class.

To start our classification, we identified 3 macro-classes of ROI

- Macro-class of rock, that includes the following classes of rocks (Figure 4):

  a. Area taken from a double facing "wall structure" in the district of Santa Venera;

  b. Area from emerging structure "Building 10", the biggest structure in the area, with a different spectral signature than the "Building 1"'s one.

  c. Area from the floor of "Building 4";

  d. Area from emerging archaeological structures called "Building 1";

- Macro-class of road;

- Macro-class of vegetation.

These last two macro-classes are defined exclusively to create spectral separability between the pixels in the image and to "train" the software, but they are not important for the research of archaeological remains. Once the training phase is over, the assignment phase is carried out by comparing, through specific classification algorithms, the spectral signature of the generic pixel to be classified with the spectral signatures of the previously created training areas.

Over the years, a huge number of algorithms have been developed. Analyzing the spectral signatures of the classes and the ROI's scatter plot, it seems that

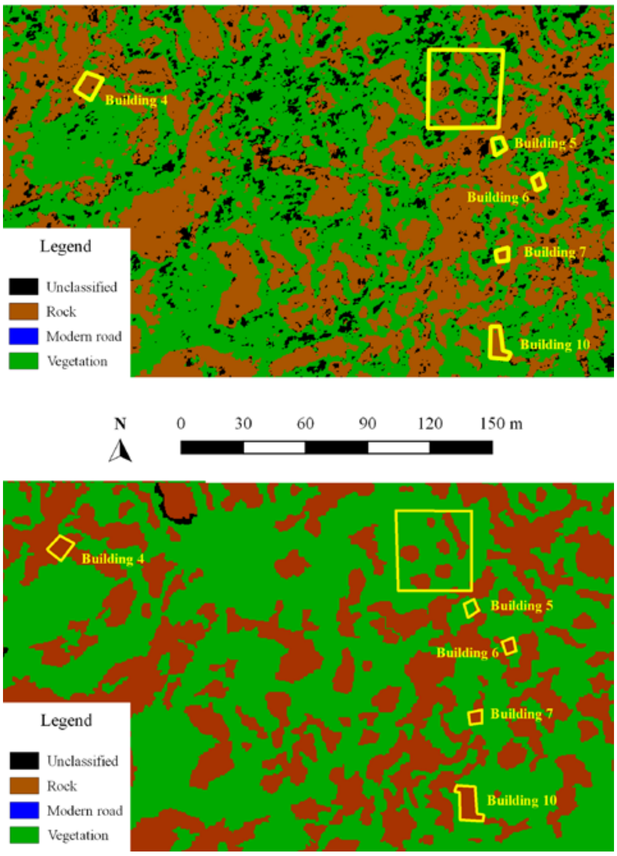

Figure 6. Comparison between pixel-based and object-oriented classification.

the Minimum Distance algorithm could be considered as the best one for our context and our purpose.

After completing the classification assignment phase, we move on to the last phase of the classification: validation phase. It consists in ascertaining the final accuracy of the produced image, realized by comparing the 'test area' with what the classifier has provided for the same locations.

Therefore, several test areas were identified in order to evaluate the accuracy of the image obtained from the classification.

Object Based Classification

In contrast to the pixel-based approach, an object-based image analysis (also called OBIA) uses the entire image or data set and breaks it down into meaningful segments (Blaschke et al. 2014). Generally, object-orientation is a programming paradigm based in the concept that the functions which are applied to data shall be assigned to a certain object. Object oriented approaches are usually based on two main steps: I) first, the segmentation, which consists in the delineation of homogenous regions in a data set; II) then, the classification, controlled by a knowledge base that describes the characteristics of output object classes (Lasaponara et al. 2016). In fact, based on initial segmentation, the single segments (i.e. sets of pixels) containing information about pixel values, object shape and topology are the input in the classification step (Benz et al. 2004). As the classified objects of interest can be used seamlessly in a GIS, OBIA is known as a technique combining remote sensing and GIS analyses (Rutzinger et al. 2006). Due to the complexity of data sources, creating a model or a "computer-based representation" is often a challenging task.

In archaeology, object-based image are discriminated not only on the different geometric and spec-

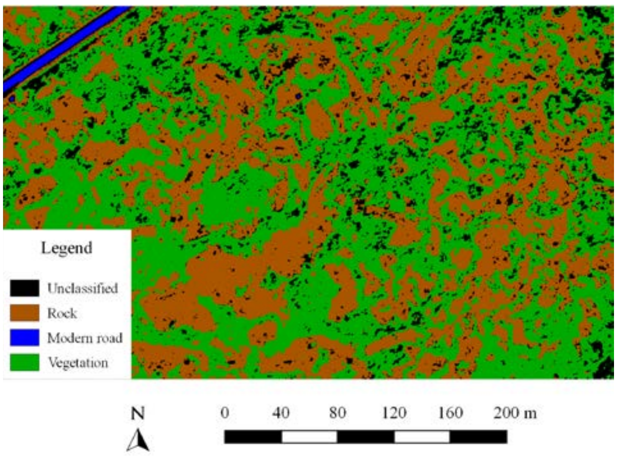

Figure 7. Pixel-based classification.

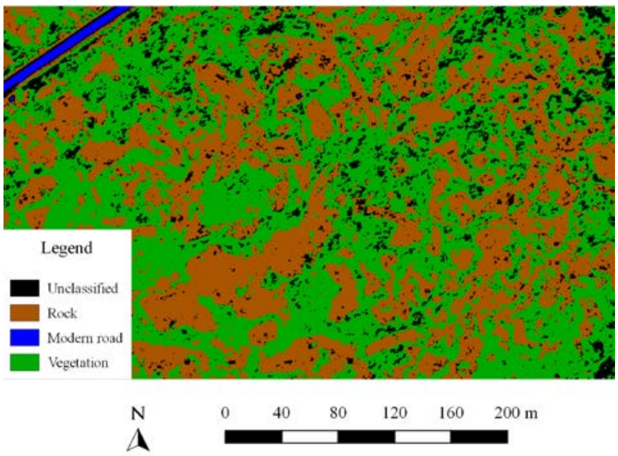

Figure 8. Object-based classification.

tral properties but also because of their semantic meaning and their association within dataset. OBIA techniques should not be used as a substitute for archaeological interpretation, but they can nevertheless increase productivity especially when dealing with large datasets. Our analysis was designed specifically for archaeological purposes. Our primary goal was to distinguish vegetation from volcanic rock and, then, identify regular shapes possibly linked to archaeological buildings. In particular, we focus on circular and rectangular shapes since the main interest of our investigations is the detection of these geometric shape features. We already know where archaeological evidence are located, because they have been already brought to light years ago. In this way, the post-dictive approach, as already stated by scholars (De Guio 2015), allows us to evaluate instruments and techniques at our disposal, emphasizing weaknesses and strengths. We performed the OBIA classification using eCognition software. In order to make archaeological feature pattern more easily recognizable, we used Red Edge, NIR-1 and NIR-2 bands.

Image Segmentation

The main aim of this phase is to find the optimal parameters for segmentation and extraction of rocky buildings using a Multiresolution Segmentation (MS), which is a segmentation technique provided by eCognition. Because MS is a bottom-up region-merging technique, it is regarded as a region-based algorithm. MS starts by considering each pixel as a separate object. Subsequently, pairs of image objects are merged to form bigger segments (Darwish, Leukert & Reinhardt 2003). The merging decision is based on local homogeneity criterion, describing the similarity between adjacent image objects. The pair of image objects with the smallest increase in the defined criterion is merged. The process terminates when the smallest increase of homogeneity exceeds a user-defined threshold (so called Scale Parameter – SP). Therefore, a higher SP will allow more merging and consequently bigger objects, and vice versa. The homogeneity criterion is a combination of color (spectral values) and shape properties (shape splits up in smoothness and compactness) (Darwish, Leukert& Reinhardt 2003). In particular, the value “one” on the color side will result in very fractal segments with a low standard deviation for pixel values, whereas a zero color value would result in very compact segments with higher color heterogeneity (Lasaponara et al. 2016). Furthermore, the shape parameter controls the shape features of an object by simultaneously balancing the criteria for smoothness of the object border and the criteria for object compactness.

Summing up, the segmentation process can be managed and modified by the three parameters seen: (i) scale (ii) shape/color and (iii) compactness/smoothness. Applying different combinations of these parameters, the user is able to create a hierarchical network of image objects. The configuration of the parameters depends on the desired objects to be segmented and, at the same time, segmentation does not have a unique solution, changing the scale parameters in multi-resolution algorithm can cause different solution; when the segmentation scale is not appropriate, the image can be under or over segmented.

In our analysis, we selected the three parameters and evaluated the goodness of the segmentation carried out, through a systematic trial-and-error approach validated by the visual inspection of the quality of the output. It is also possible to proceed with the classification process and then indirectly assess the goodness of segmentation process through the accuracy of the classifications produced (Darwish, Leukert& Reinhardt 2003). In order to make archaeological feature pattern more easily recognizable, in this step we have used Red Edge, NIR-1 and NIR-2 bands. In particular, we have taken SP equal to 25, shape/color equal to 0.85 and compactness/smoothness equal to 0.25. This means that 85% of the criterion dependent on shape and 15% on color. The shape factor was divided between compactness and smoothness in the ratio of 1 to 3. The results of the segmentation process are shown in Figure 5.

Image Classification

The segmentation results have fundamental implications because they form the basis of the subsequent classification; in this phase, classes are defined and each individual segment is assigned to a single class based on the employed target object’s properties.

In the present case study, we selected the same thematic classes and the same ROIs used for pixel-based

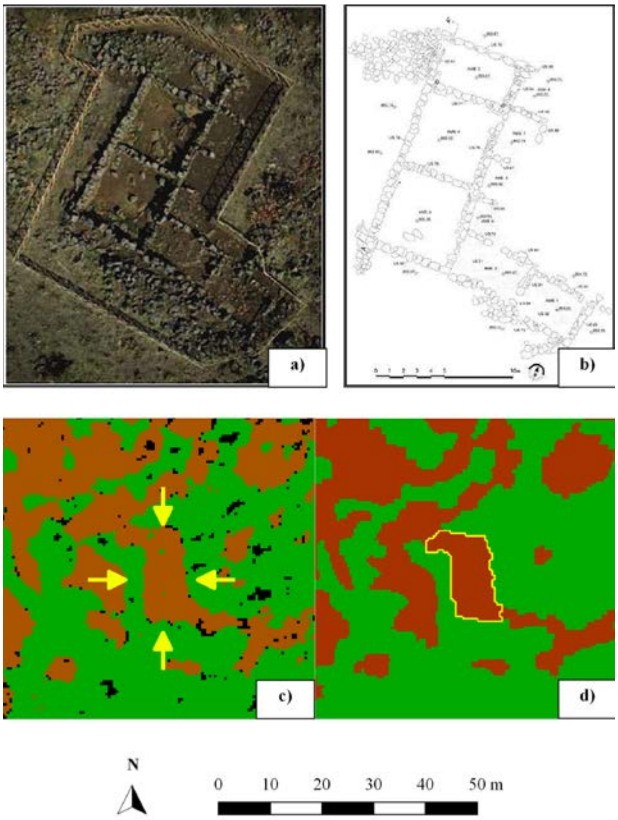

Figure 9. Building 10 from two different classifications: pixel-based (left), object-based (right).

classification. This will allow us, with the same boundary conditions, to make a comparison between the pixel and object approach applied to the particular context under examination. Like pixel-based classification, once the training phase is over, the next phase is assignment. However, unlike what is seen with the pixel-based classification, this assignment phase is performed using specific classification algorithms, which take into account not only the spectral characteristics of the previously created training objects, but also the geometric and topological features. In our analysis, we have used the Nearest Neighbor algorithm, which seems to be the best for our context. In particular, this algorithm has been appropriately calibrated to perform the classification taking into account both the spectral characteristics and the geometric ones (appropriately identified for the particular context under examination). The last phase of the classification is the validation phase, which consists in ascertaining the final accuracy of the produced image by comparing the 'test area' with what the classifier has provided for the same locations.

Results and Discussion

Now we want to compare the results from both traditional pixel-based and object-oriented classification. It is worth mentioning that the legend used is the same used for both approaches: this facilitates the comparison (Figure 6).

Pixel-based method allows us to classify emerging walls and structures especially, while other archaeological features were not correctly detected (Figure 7). In particular:

Building 10 is clearly recognizable also because it's the biggest and best conserved building;

with regard to Building 3, it is possible to identify just the emerging North-Western wall.

Building 4 is clearly recognizable, despite the modest dimension and the fact that it is mostly buried for its circular shape;

Buildings 5-6-9 cannot be easily distinguished from the surrounding lava rock; probably, the structures were built in that peculiar position in order to use the lava hill as a form of northern and cold wind protection; the "wall structure" in Santa Venera district is easy to recognize also because either its length and its wall's thickness.

Analyzing the results obtained, it is clear that the classification achieved through the minimum dis-

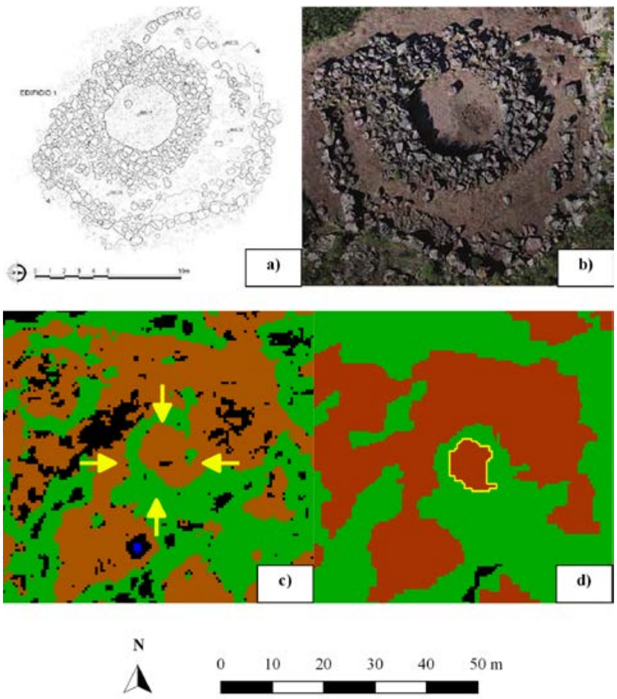

Figure 10. Building 1 from two different classifications: pixel-based (left), object-based (right).

tance algorithm has an overall accuracy of 45%. Also from the value of Cohen's Kappa it is clear that the classification is middling.

A further analysis of this value showed that one of the main problems is the classification of small objects, whose contrast to the surrounding environment is low. This is one of the most challenging problems, especially examining our situation. First of all, archaeological buildings have small dimension, considering that the biggest one is approximately 100 square meters. In addition, the material used for the construction of huts is not brick but, unfortunately, lava stone. So, we were looking for wall and structures made by volcanic stone in a volcanic plateau.

The final results of the object-based classification are shown in the following image (Figure 8).

Unlike what was obtained with the pixel-based approach, in the object-based procedure only a few of the archaeological buildings remained difficult to recognize, while most of them were detected correctly, despite the dense vegetation and the complex environment. In particular, the buildings already recognizable in the pixel-based classification map (such as the building 10, 4 and the wall structure) are here even better identified and defined (Figures 9 & 10). In addition, buildings that were not clearly recognizable in the pixel-based classification map (such as buildings 3, 5, 6 and 9) are more easily identifiable here

The positive final outcome is certainly to be found in the segmentation phase, in which operating with three types of parameters, adopting a trial-and-error approach, it is possible to segment the entire scene; so, the subsequent classification phase will be performed on objects and not simply on pixels. In addition, the classification algorithm used here takes into account not only spectral features, but also features related to the created objects (i.e. geometry, shape, etc.). All these elements allow us to obtain a thematic classification map characterized not only by a higher OA, but also by the absence of the classic "salt and pepper" effect typical of a pixel-based classification.

Although the object-based classification is considerably more accurate than the respective pixel classification, some unresolved issues remain. In fact, even if with a smaller entity, the problem concerning the classification of small buildings with a low contrast with the surrounding environment persists. As we have already mentioned above, this issue is closely related both to the size of the archaeological buildings sought and to the material with which the huts are made. In fact, the huts are not made of bricks but, unfortunately, of lava stone.

Conclusions

This paper has outlined two strategies for the semi-automated extraction of archaeological features from multispectral data, comparing the results of pixel and object-based approaches in the same archaeological environment.

The results discussed above represent a positive step forward for recognizing the value of different approaches. However, as we have demonstrated here, the use of an automated classification algorithm, as a complete substitute for manual interpretation, would result in a series of errors.

The final outcome is even more critical taking into account the pixel-based classification, where a number of archaeological buildings have not been classified in the correct way. The main issue deals with the problem of separating, using spectral signature, lava rock from archaeological structures made of lava stonewalls. In addition, many variables, as environmental conditions, greatly reduce successful classification rates.

In the object-based procedure, just few of the archaeological buildings remained hard to recognize, while most of them were detected correctly. The post-dictive approach, with targeted detection and classification of known classes already in mind, clearly helped in obtaining a good performance.

So, at least automatic identification of archaeological features procedure provides a functional benefit in a time-saving perspective, reducing the necessity to manually digitize features. In addition, rapid detection of potential objects of interest can be a perfect starting point for more detailed and subsequent interpretations.

In our opinion, the development of semi-automated techniques for the analysis of remote sensing data is priority and what this work makes evident is that the skilled interpreters role will be crucial to any process. Clearly, we still need to create general framework for archaeological feature detection in specific contexts, especially for the volcanic one here presented, without having to rewritten rulesets completely.

References

Bennet, R, Cowley, D & De Laet V 2014 The data explosion: tackling the taboo of automatic feature recognition in airborne survey data. *Antiquity*, 88 (341): 896-905.

Benz, U, Hofmann, P, Willhauck, G, Lingenfelder, I & Heyen, M 2004 Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS Journal of Photogrammetry and Remote Sensing*, 58: 239-258.

Blaschke, T, Hay, G, Kelly, M, Lang, S, Hofmann, P, Addink, E, Queiroz Feitosa, R, Van der Meer, F, van der Werff, H, van Coillie, F & Tiede D 2014 Geographic Object-Based Image Analysis – Towards a new paradigm. *ISPRS Journal of Photogrammeetry and Remote Sensing*, 87: 180-191.

Calderone, D, Mangiameli, M, Mussumeci, G & Palio, O 2022 Multispectral satellite imagery processing to recognize and analyse archaeological sites in the central area of Sicily (Italy). *Journal of Archaeological Science, Reports* 44 (08-2022) No. 103514.

Candiano, A, Fargione, G, Gennaro, A, Mangiameli & M, Mussumeci, G 2019 Experimental band combination of multispectral satellite imagery for the analysis and classification of archaeological features. In: Simos, T & Tsitouras, C (eds.): *AIP Conference Proceedings 2019. ICNAAM, 13-18 September, Rhodes, Greece,* vol. 2116, https://dx.doi.org/10.1063/1.5114285

Consoli, A 1988-1989 Bronte-Maletto. Prima esplorazione e saggi di scavo archeologico nelle contrade Balze Soprane, Santa Venera, Edera e Tartaraci. *BCA Sicilia*, IX-X (3): 74-79.

Darwish, A, Leukert, K, & Reinhardt, W 2003 Image segmentation for the purpose of object-based classification. *Geoscience and Remote Sensing Symposium, 2003 Proceedings. IEEE International,* 3: 2039-2041.

De Guio, A 2015 Nuove linee di ricerca fra archeologia pre-dittiva e post-dittiva. *Archeologia e Calcolatori*, 26: 301-313.

De Laet, V, Paulissen, E, & Waelkens, M 2007 Methods for the extraction of archeological features form very high-resolution Ikonos-2 remote sensing imagery, Hisar (southwest Turkey). *Journal of Archeological Science*, 34: 830-841.

D'Orazio, T, Palumbo, F, & Guaragnell, C 2012 Archelogical trace extraction by a local directional active contour approach. *Pattern Recognition*, 45: 3427-3438.

Ganci, G, Cappello, A, Bilotta, G, Corradino, C, Mangiameli, M, Mussumeci, G & Del Negro, C 2020 3D lava flow mapping in volcanic areas using multispectral and stereo optical satellite data. In: Simos, T & Tsitouras, C (eds.): *AIP Conference Proceedings 2020. ICNAAM,23-28 September 2019, Rhodes, Greece*, vol. 2293, https://doi.org/10.1063/5.0027312.

Gennaro, A, Candiano, A, Fargione, G, Mussumeci, G, Mangiameli, M 2019 GIS and remote sensing for post-dictive analysis of archaeological features. A case study from the Etnean region (Sicily). *Archeologia e Calcolatori*, 2019, 30: 309–328.

Gennaro, A, Candiano, A, Fargione, G, Mangiameli, M & Mussumeci, G 2019b Multispectral remote sensing for post-dictive analysis of archaeological remains. A case study from Bronte (Sicily). *Archaeological Prospection*, 2019, 26 (4): 299–311

Gennaro, A, Mangiameli, M, Muscato, G, Mussumeci, G & Sgarlata, M 2018 Geomatic techniques for surveying and mapping an archaeological site. In: *IEEE International Conference on Metrology for Archaeology and Cultural Heritage 2018, (MetroArchaeo 2018) Proccedings. IEEE*, pp: 277–281.

Guidoboni, E, Ciuccarelli, C, Mariotti, D, Comastri, A & Bianchi, M G 2014 *L'Etna nella Storia. Catalogo delle eruzioni dall'antichità alla fine del XVII secolo*, Bologna: Bononia University Press-Istituto Nazionale di Geofisica e Vulcanologia.

Lasaponara, R, Leucci, G, Masini, N & Persico, R 2014 Investingating archeological looting using satellite images and georadar: The experience in Lambayeque in North Perù. *Journal of Archeological Science*, 42: 216-230.

Lasaponara, R, Leucci, G, Masini, N, Persico, R & Scardozzi, G 2016 Towards an operative use of remote sensing for exploring the past using satellite data: The case study of Hierapolis (Turkey). *Remote Sensing of Environments*,174: 148-164.

Leone, A, Witcher, R, Privitera, F & Spigo, U 2007 The Upper Simeto Valley. An interim report on the first season. In: Fitzjohn, M (ed.) *Uplands of ancient Sicily and Calabria. The Archaeology of Landscape revisited*, London: Accordia Research Institute, pp. 43-64.

Mangiameli, M, Candiano, A, Fargione, G, Gennaro, A & Mussumeci, G 2020 Multispectral satellite imagery processing to recognize the archaeological features: The NW part of Mount Etna (Sicily, Italy). *Mathematical Methods in the Applied Sciences*, 2020, 43 (13): 7640–7646.

Mangiameli, M, Mussumeci, G, Candiano, A 2018 A low cost methodology for multispectral image classification. *Lecture Notes in Computer Science*,1096 DOI: 10.1007/978-3-319-95174-4_22.

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Stereo-Satellite Imagery for the Creation of DEM and Topographic Maps to Support Site Management of the UNESCO World Heritage Minaret of Jam (Afghanistan)

Georgios Toubekis
Fraunhofer Institute for Applied Information Technology – FIT, Sankt Augustin
georgios.toubekis@fit.fraunhofer.de

Albert Moll
Geoscientific Applications (GEOSCAP), Cologne
info@geoscap.com

Michael Jansen †
Research Center Indian Ocean [RIO], German University of Technology, Halban-Muscat, Oman

Matthias Jarke
Fraunhofer Institute for Applied Information Technology – FIT, Sankt Augustin
matthias.jarke@fit.fraunhofer.de

Abstract

Remote sensing techniques for the management of cultural heritage sites in Afghanistan have been applied successfully in recent years because the security situation at the ground does not allow activities in the field. Advanced remote sensing technologies were used to generate elevation data from high-resolution satellite stereo-imagery of the Ikonos sensor for the generation of accurate topographic maps. Additional very high-resolution imagery of the WorldView-2 sensor was used to produce orthorectified image maps that facilitate local site management. Terrestrial measurements from previous field surveys were used for image geo-referencing and validation of the DEM from the stereo-imagery. Elevation points were derived in a semi-automatic process and adjusted by stereo-inspection through a human operator. Contour lines and shaded relief maps are created in the next step to be combined with findings from previous archaeological surveys. The superposition of all available information indicates that the existing boundaries of the World Heritage property and buffer zone are to be adjusted. The resulting maps serve as a planning base for future development activities, such as the enforcement of the river embankment to protect the minaret from flooding. The analytical data also serve for future numerical studies of the flooding regime at this particular place. It is argued that all data and cartographic products are required in such complicated cases with access restrictions for intensive fieldwork and should be considered in similar cases by researchers and planners. All activities form part of the international efforts to establish a protection scheme supporting the long-term management and the preservation of the World Heritage property.

Keywords: Remote Sensing, Word Heritage, Site Documentation and Management

Introduction

The management of Cultural Heritage in war-torn countries like Afghanistan remains a challenging task. The Ministry for Culture and Information of the Islamic Republic of Afghanistan holds two institutions to take care of the management of cultural heritage in the country. The Department for the preservation of Historical Monuments (DoHA) and the National Institute of Archaeology (NIA) both share management responsibilities for the tangible heritage. Therefore actions in the field require additional coordination efforts to minimize overlapping areas of activities. Besides the ongoing security issue affecting free movement in large parts of the country, the technical and human resources on the national level remain limited, not only in the culture sector. It will require another generation to be trained for that sufficient scientific expertise is gained to participate in the scientific discourse on an international level. Therefore after the fall of the Taliban regime, the international community pledged for assistance to the rehabilitation of the cultural heritage sector of the ravaged country initiating an international safeguarding campaign coordinated by UNESCO (ICC 2003). A priority action since has been the support for two of the most important sites in the country the Minaret and Archaeological Remains of Jam, and the Archaeological Remains and the Cultural Landscape of the Bamiyan Valley inscribed in 2002 and 2003 as World Heritage under the Convention Concerning the Protection of the World Cultural and Natural Heritage (UNESCO 1972). Out of these, the Minaret of Jam is renowned for the elaborated brickwork construction partially covered with excellent tile work dating from the 12th century. The noteworthy quality of its architecture and decoration, which according to the nomination, represents the culmination of an architectural and artistic tradition in this region is further heightened by its dramatic setting, a deep river valley between towering mountains in the heart of the western Ghur province in Afghanistan (Figure 1).

Both nominations reactivated a process that was initiated already as early as 1982 when the Outstanding Universal Value (OUV) of the sites was already confirmed by the World Heritage Committee, allowing for a rather hasty nomination procedure. The information on the provisional management system, the boundaries and buffer zone for the inscribed property were defined and marked on a map.[1] Boundaries are supposed to follow the contours of the topographical character of the area but are based on outdated topographic maps, raising the concern of ICOMOS in the evaluation of the nomination dossier. Besides, the rather unusual cartographic format, the provided map omits any information concerning more recent or contemporary interventions in this area (including the route of new road constructions under discussion). ICOMOS recommended for the State Party to provide more detailed and accurate cartographic materials to meet these deficiencies (ICOMOS 2002).

The identification of a World Heritage property´s boundaries and an appropriate buffer zone are mandatory according to the Operational Guidelines to the World Heritage Convention. They are considered necessary for the adequate protection and management of sites, but methodologies for their definition may vary following established best practice examples (Martin and Piatti 2009). Therefore the shortcomings in the nomination dossier also reflect the identified needs for further technical assistance to the State Party after more than 25 years of military conflict. To this extent, the maps submitted in the initial nomination dossiers in 2002 and 2003 respectively had to be updated in order to include the latest information available on the extent of the archaeological remains at the site of Jam. The work presented in this paper is part of a larger project within the UNESCO efforts for the preservation of the World Heritage Sites of Jam and Bamiyan and describes the creation of a topographic map for site management purposes based on the analysis of high-resolution satellite imagery.

The Minaret of Jam

The Minaret of Jam (Lat. 34°23’47.6 N, Long. 64°30’57.8 E) is one of the few surviving monuments of the little known Ghurid sultanate, which lasted from the end of the 12th to the beginning of the 13th century CE (Ball 1982). It is regarded as the second tallest ancient minaret in the world, surpassed only by the Qutb Minar in Delhi, which was also built by the Ghurids (Pinder-Wilson 2001). The site of Minaret of Jam is located at the confluence of the Hari Rud with one of its tributaries the Jam Rud (rud [persian] = torrent, river) in the very remote mountainous region of Ghur in Western Afghanistan some 215 km east of Herat at an elevation of around 1900m.

The impressing view of the minaret draws off attention from archaeological remains that are scattered on the steep mountain surface on both sides of the Hari Rud. Buried from erosion, the remains of structures can be traced pin-marked by the existence of holes resulting from illegal excavation activities going on for decades. The minaret structure is rising from an octagonal constructed base, with four superimposed, tapering cylindrical shafts all build from fired bricks. The geometric pattern of the surface of the Minaret consists of delicate haut-relief brickwork visually enhanced with a Kufic inscription in light-blue turquoise tiles at its higher parts. Constructed at some time between 1174 or 1194 CE, the

1 The initially submitted map for Jam is available at http://whc.unesco.org/en/list/211/multiple=1&unique_number=234 and for Bamiyan at http://whc.unesco.org/en/list/211/multiple=1&unique_number=230

Figure 1. View of the Minaret of Jam from the south with remains of a castle on the ridge and partly open pits resulting from illegal excavations at the northern slope of the river.

minaret survived considerably well preserved to our days, including its remarkable double helix internal staircase. The quality of its architecture and decoration represents the culmination of an architectural and artistic tradition in this region.

Scientific Exploration and Conservation Activities at the Site and its Surroundings

Since the time of the first scientific explorations of French archaeologists in 1957, it has been suggested that the site probably marks the ancient city of Firuzkuh, the capital of the short-lived Islamic Empire of Ghur that at its height covered a territory from today Western Afghanistan down to the Bay of Bengal until was swept away by the Mongol raid of its capital in 1222 (Maricq and Wiet 1959). A comprehensive summary of the history and the understanding of the site until its inscription as World Heritage is given in (Sourdel-Thomine 2004).

More recently, the research at the site is embedded in the context of the UNESCO preservation activities following the World Heritage nomination. Object finds during limited archaeological field surveys testify the presence of extraordinary luxury goods at this place (Thomas et al. 2004). The collection of this archaeological data was realized in the Minaret of Jam Archaeological Project (MJAP) by the Istituto Italiano per l'Africa e l'Oriente, on behalf of UNESCO and the National Afghan Institute of Archaeology (NAIA) initiated in preparation for a future management plan. Findings yielded rich environmental and geomorphological data that provided the first direct evidence to support the historical account of the "Masjid-i Jami" at Firuzkuh being washed away in a flash flood (Thomas et al. 2006).

The inclination of the minaret of around 3.4° towards the riverbank on its northside is still not explained satisfactorily (Borgia 2002) but raises constant concern on its stability. Therefore with funds from UNESCO within the international support project Emergency Consolidation and Restoration of the Monuments in Herat and Jam in Afghanistan, a series of emergency preservation actions at the site were initiated. The inclination causes an asymmetrical load distribution, which results in overload at the north-northwestern side and decompression at the opposite side. This overload causes horizontal stresses in the brick masonry, resulting in vertical cracks in walls and bricks that may be consistently increased by seismic effects. Therefore, a seismic hazard assessment was done that concluded seismic input not to be the factor governing the structural vulnerability of the minaret, since the highly seismic, subduction zone of the Hindukush region yielded negligible effects at Jam in terms of seismic hazard so far (Menon, Lai and Macchi 2004).

For the long-term preservation of this monument, retrofitting measures were considered to increase the overall structural integrity of the minaret under normal gravity load. Also, massive erosion of the minaret´s base indicates severe flood events during the last eight centuries. Therefore, the lower exterior brick surface was reinforced, and consolidations of the river banks were realized to mitigate the impact of high-rise river waters. Protecting the base of the minaret is regarded as a critical stabilizing measure preventing any further increase of the inclination. A complete overview of these activities is given as an Open-Access publication by UNESCO (Han 2015),

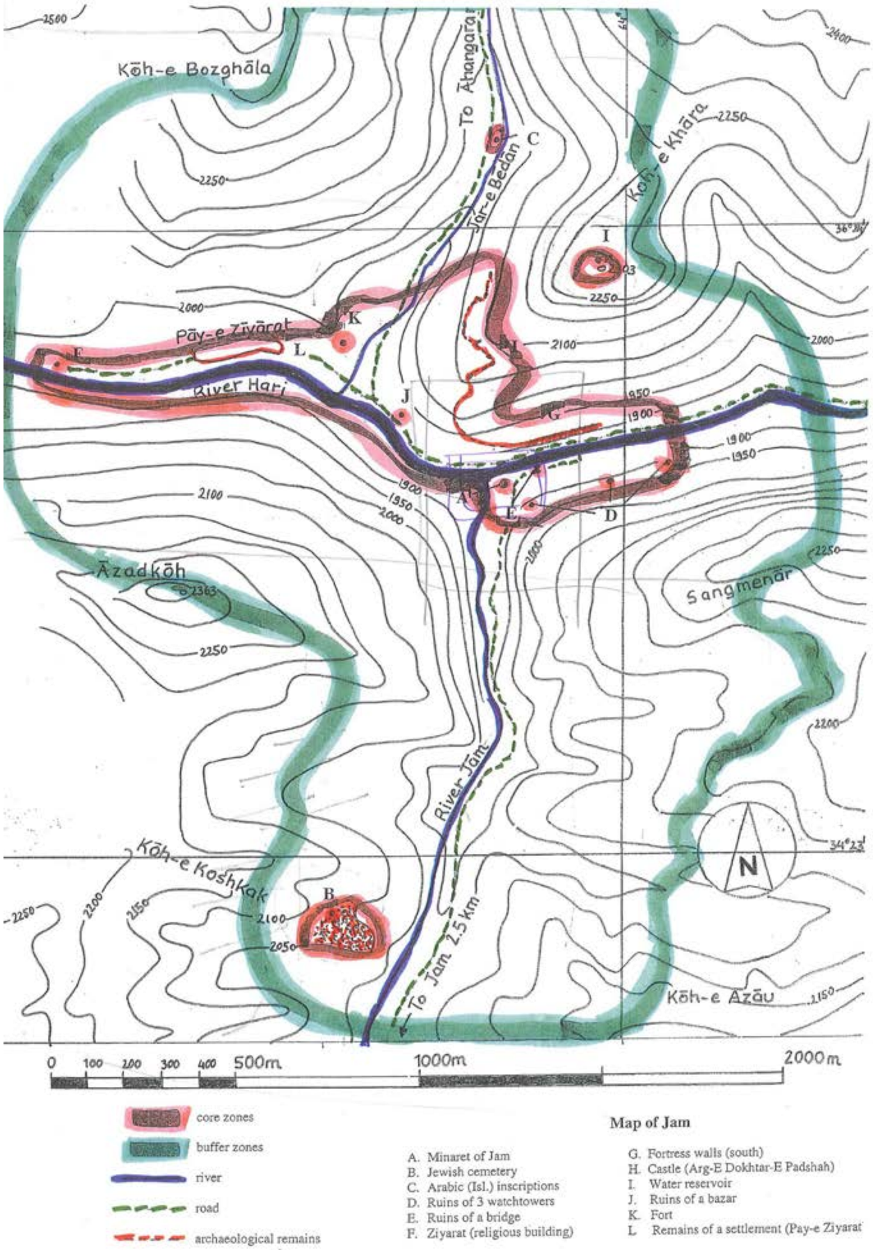

Figure 2. Topographical map of the site as of 2002, the four isolated „core" areas (red colour) surrounded by a large buffer zone (green) taken from the nomination file (UNESCO World Heritage Centre 2002).

and the authors have compiled the resulting detailed technical reports for future reference (Toubekis et al. 2014).

Mapping Documentation of the Site

In 1973 Werner Herberg and Ghulam Djelani Davary provided accurate hand-measured drawings on the structure of the minaret, and a very basic overview map concluded from large-scale topographic maps available at the time. Already at that time, it is assumed that the entrance to the minaret and its entire foundational base is engulfed in alluvial deposits with a thickness of around 4–6 m, forming a terraced plain above the original river bed. This documentation (Herberg and Davary 1976) also included information on a cemetery two kilometres south of the minaret on a hilltop along the Jam Rud with Judeo-Persian epitaph inscriptions in Hebrew script.[2] Towards the north on the other side of the Hari Rud up the ridge on a first plateau, the remains of an apsidal room partly dug into the rock are considered to have served as a water reservoir. Also, the

2 Beside the factual evidence for a Jewish settlement in this area the tombstone inscriptions are indicating towards burials that have taken on a regular basis in the years between 1012 CE until 1220 CE two years before the siege of Firuzkuh by Mongol troops.

List of Standpoints UTM Zone 41N Datum: WGS 84	E063…. Easting (X) in m	N380…. Northing (Y) in m	Ellipsoid Height (Z) in m
101	9357.000	7168.000	1905.000
102	9619.815	7243.653	1901.962
103	9303.959	7231.793	1903.454
104	9369.013	7203.788	1902.831

Table I: List of permanent fix-points and their coordinates at the site of Jam as installed in 2002 and re-established in 2006 (Stevens 2006).

remains of a fortification are visible directly above the confluence of the two rivers surrounded by some modern time houses and further eroded archaeological remains stretching up the hills. All this scattered information has been included in the baseline information for the World Heritage nomination of 2002, resulting in a property composed of four isolated "core" areas (Figure 2).

In preparation for conservation activities on the ground, more precise topographic information and a complete mapping of the site was required. Therefore within the UNESCO safeguarding project as a first measure, a UNESCO mission set out to produce a preliminary map of the site's main features in the terrain and to precisely capture the inclination of the Minaret with reflectorless total station measurements. A local reference system was established, and the geographic coordinates for the initial fix-point 101 were acquired by handheld GPS device resulting in an absolute positional accuracy for this point within the range of some meters. Additional fix-points measured with mm-accuracy referenced to the initial fix point were set up permanently into the ground to ensure the comparability of measurements in the long-term. The measurements showed inclination variances between 3.47gon to 3.97gon (3.13° - 3.57°) for the various shafts with the upper part of the minaret leaning 3.128m out the central axis of the structure having the top of the inclined minaret at 60.41m above the ground at the northern site (Santana Quintero and Stevens 2002). During a monitoring mission in 2006, the inclination of the minaret was controlled, and the local reference system (see Table 1) served as an indicator of quality. Although some of the previous fix-points and secondary reference points had been unearthed and the reference system needed to be re-established again before the new measurements (see Figure 3), the monitoring revealed that in the time interval of four years, no measurable change in the inclination of the minaret took place. The mission also included a component of training for the national staff of the Afghan Department of Historical Monuments in high precision measurement techniques with a total station. A standardized protocol was introduced to monitor the correct location of the fix-points and the inclination of the minaret in the future by measuring some control points installed on the brick surface (Stevens 2006).

The difficulty in access and the overall congested security situation in the country has been disadvantageous in establishing a functioning management system at the site from the beginning. The presence by personnel of the national heritage administration has been limited to some police guards to prevent the looting of the area that has occurred in the past.

The lack of appropriate topographic information that covers the entire valley and the vicinity of the minaret at an appropriate scale has been an obstacle both to the accurate documentation of the small-scale emergency excavations along the riverbed and also for the large-scale riverbank protection measures that were realized within the UNESCO program after a massive flood occurred in 2007. Due to the deteriorating security situation, the activities executed could not be assisted by international experts and did not allow for further survey mission to be realized in the coming years. The significance of the Minaret of Jam has resulted in the necessity to improve the management system, primarily to indicate the extent of the protected areas precisely on the ground.

The efforts for the preservation of the site are challenged, especially in the context of economic development pressure, resulting from envisioned road constructions to connect the remote villages in the

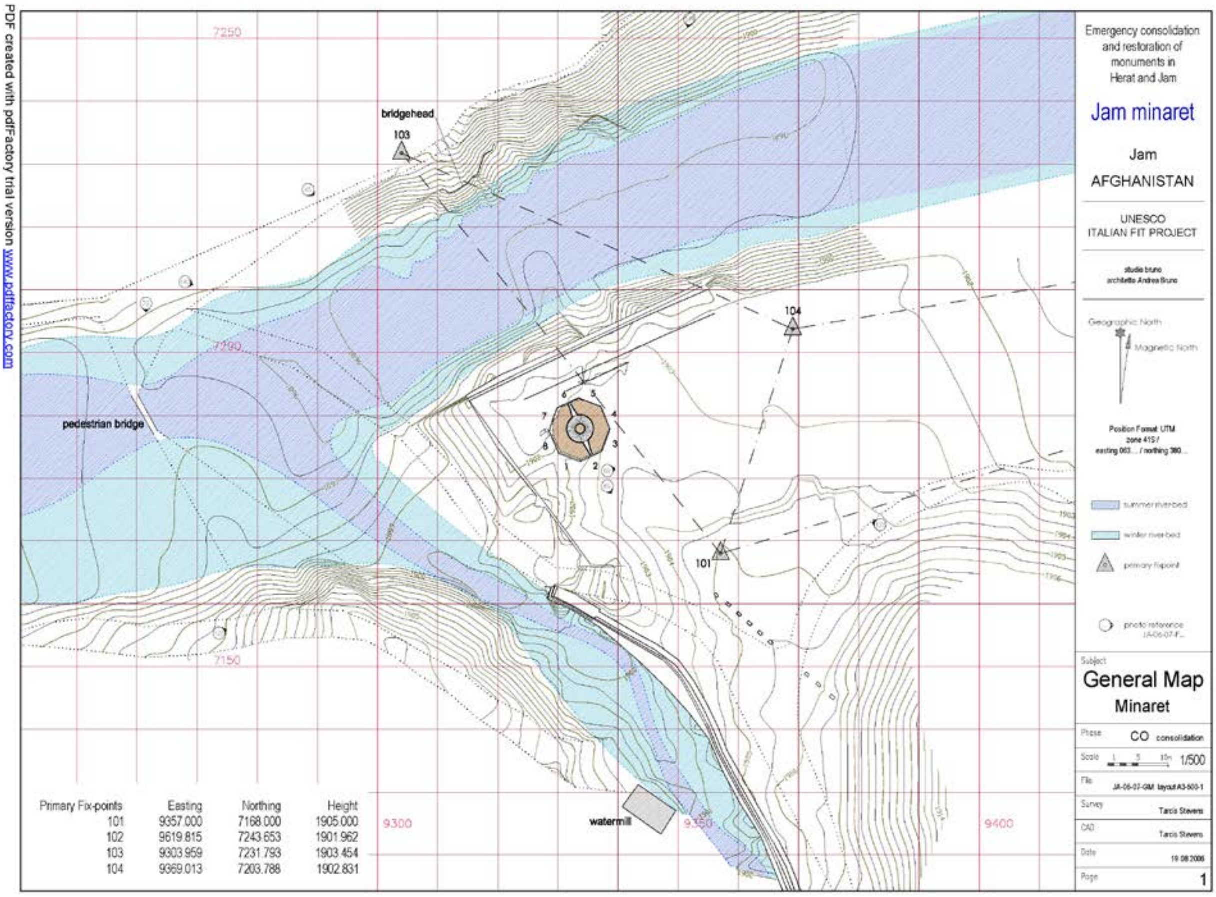

Figure 3. Topographic map with the location of fix-points in the ground (from Stevens 2006).

vicinity of the minaret, passing directly through the valley. In order to realize a detailed topographic map with sufficient information on the entire site and its surroundings new methodologies from the domain of remote sensing for documentation of cultural heritage sites were applied in the period 2010-2012.

Generation of Topography and Sitemap Based on Remote Sensing Techniques

High-Resolution remote sensing techniques refer to the remote viewing of the world surrounding us by satellite sensors, usually from low-earth orbits (600-800km height). Remote sensing in cultural heritage management is used to determine anthropogenic features in the real world. The mapping methodology includes landscape features but also built structures such as roads, settlements, and individual buildings or monuments and sites. Satellite remote sensing has the advantage of being able to see an entire landscape at different resolutions and scales (Comer and Harrower 2013).

Methodology

Since the aim was to obtain a map at a sufficient high scale to allow for planning of activities at the site, publicly-available satellite imagery via Internet services such a Google Earth or Microsoft Bing were opted out because they did not meet the requirements for reliable topographic information. In contrast, stereo-images allow exploring the scene in three dimensions. With photogrammetric calculations based on real distances and heights known at the ground, it is possible to extract accurate 3D spatial information for the entire image scene, a so-called Digital Elevation Model (DEM), from which precise topographic map information can be generated.

The generation of a DEM by photogrammetric methods is based on the evaluation of the individual images acquired under different viewing geometries (Kraus and Harley 2007). The same points have to be identified in both images referred to as stereo pairs.

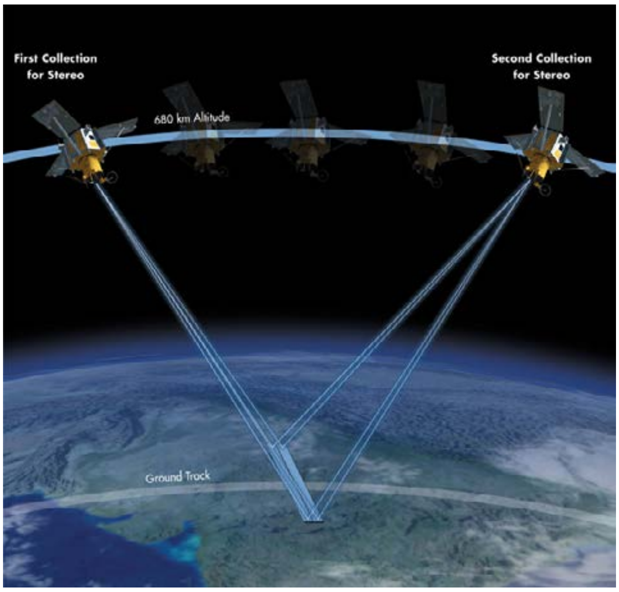

Figure 4. Acquisition method for capturing the topography with high-resolution stereo-image pairs of a linear array CCD sensor that takes images with one overfly. Same pass stereo pairs are advantageous for subsequent processing such as feature extraction because the scene content and lighting conditions are virtually the same for the two images. (Image courtesy Satellite Imaging Corporation).

The differing spatial positions of these homologous points in a stereo pair reveal information about their elevation at this point. The procedure is similar to conventional photogrammetry practised in architectural recording for decades and standard practice in the visual stereo-analysis of analogue aerial image interpretation. In the digital era, however, for automatic image analysis, specialised software, specific photogrammetric skills, and experience are required to obtain useful results (Zhang and Gruen 2006).

The first step is to identify as many identical points as possible in both images. For this purpose, image matching algorithms for a single sensor type are used (Fraser, Baltsavias and Gruen 2002). Homologous points form the basis for the DEM. Their height can be calculated directly from their spatial shift by computational methods. In areas with little distortions (flat areas), many points are available. In areas with moderate or high relief, the number of points to be found in more or less reduced, as the terrain is differently imaged due to the different viewing angles of the sensor (Fraser and Yamakawa 2003). If distortions in the stereo pair exceed a specific limit, the images cannot be matched, and no identical points can be determined. The lack of homologous points is also a problem in areas that are not covered in both images, for example, areas in front of steep cliffs, which overlay the surrounding terrain. It is also a problem also in areas that are not illuminated at all because shadowing is too severe (Gruen, Remondino, and Zhang 2005).

Additional information about the geo-location is necessary to get an absolute geographical position of the points. This information can be derived from orbit parameters of the satellite allowing for a referencing accuracy of a few meters (Fraser and Hanley 2003) that can be improved with the help of ground truth data. In this work, the specific sensor camera model (Grodecki 2001) is provided as additional orbit parameters with the image metadata. Also, the topographic measurement points from the previous field campaigns (Santana Quintero and Stevens 2002; Stevens 2006) were used and served for ground-truthing. The measurement data in ASCII file format was imported to a Geographical Information System (GIS) and transformed into data shapefiles for further use in the GIS.

Acquisition of Satellite Imagery

Due to the complicated mountainous situation in the area of Jam initially, a very high-resolution scene with half-meter per pixel resolution by the commercial GeoEye-1 sensor was envisioned to be ordered. Unfortunately, the satellite provider was not able to provide such a product in the foreseen time window due to unexpected restrictions upon sensitive military areas imposed by U.S. authorities.

Therefore the initial plan was changed, and a satellite stereo-image scene was acquired in April 2012 from the IKONOS sensor (GeoStereo product in 11-Bit GeoTIFF file format, Standard Geometric Correction) covering the area of the minaret of Jam and the surrounding mountainous area with panchromatic (black and white) 1m per pixel and multispectral (blue, green, red, near-infrared bands) 4m per pixel resolution. IKONOS collects the same pass stereo pairs (see Figure 4); that is, the two images constituting the stereo pair are taken on the same orbital overfly. As the satellite approaches the target, it yaws, rolls and pitches, as required, to collect the first leg of the stereo pair while pointing in a forward direction. A hundred or so seconds later, after the first image is collected, the satellite is manoeuvred to image the same area again, this time pointing in

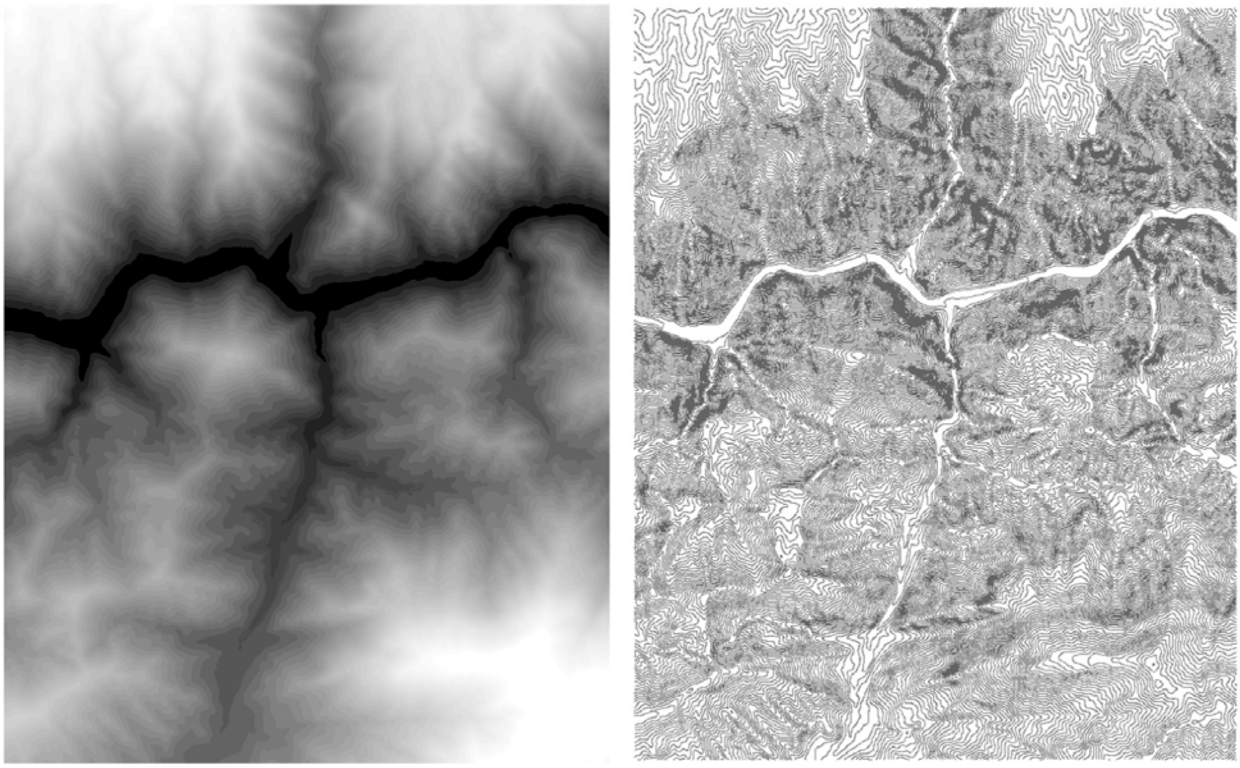

Figure 5. Topographic height information derived from the stereo images: Digital Elevation Model (DEM) as raster image dataset (left) and contour line extraction (10m) as vector dataset (right).

a backward direction (Grodecki and Dial 2001). The coverage of around 100km² resulted in images sizes of 185 million pixels (pan) and 11 million pixels (multispectral) for each image of the stereo-pair. In addition, the archive material of other high-resolution sensors was systematically consulted, and two images (no stereo) of the WorldView-2 sensor (Standard Level 2A product in 16-Bit GeoTIFF file format) were identified, subsequently orthorectified and used with a 5km x 5km (25km²) coverage area. These two images have a small overlapping region, which shows the Minaret of Jam at the edge of their respective image borders at panchromatic (black and white) 0.5m per pixel and multispectral (blue, green, red, near-infrared bands) 2m per pixel resolution. The images have different acquisition dates from March and April 2011 but with similar viewing angles and sun-light illumination conditions.

Processing of Stereo-Scene for Generating a Digital Elevation Model and Ortho-Photos

For image matching of homologous points and stereoscopic processing the ERDAS Imagine/Leica Photogrammetry Suite 9.1 was used in combination with self-programmed tools in C++ for sampling optimization. To achieve the best results, a surface reconstruction algorithm based on Laplacian partial differential equations (Franklin 2000) for interpolation of elevation data is used, giving smooth results even for areas with sparse points. For the complete area, topographic contour lines are derived mainly by an automatic process. In a final stage, a manual correction process has to be accomplished to identify points with corrupted elevation information via stereoscopic viewing. This was done by interpolating and stereoscopically identifying false points by a human operator. From about 200.000 points initially derived by image matching, about 500 points had to be eliminated, iteratively, step by step during this process resulting in a continuous spatial dataset. Elevation extraction via automatic processing was challenging for fast-changing surfaces (steep relief) and was therefore significantly improved by these manual stereoscopic operations.

The resulting DEM (see Figure 5 - left) represents the elevation, including vegetation and buildings,

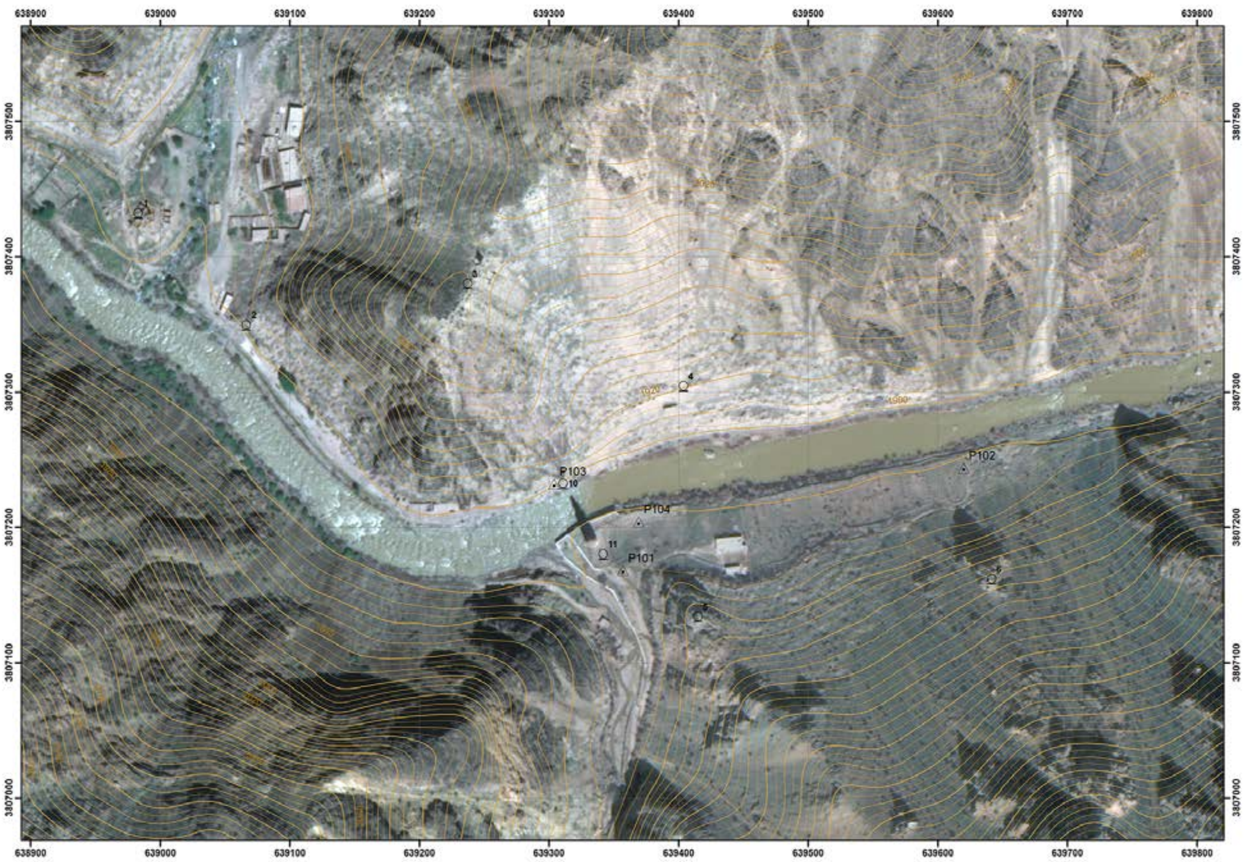

Figure 6. Extract of orthophoto map based on the fusion of two WorldView-2 images overlaid with topographic contour lines extracted from the Ikonos stereo-images (Image: by the Authors/DigitalGlobe).

not only the sole ground (i.e., a digital surface model). Small objects tend to be omitted, and large objects are more likely included in the DEM (large rocks or structures) depending on their dimension. The cell grid of the computed raster image should be small enough to capture the required detail, but also large enough to allow computer storage and analysis to be performed efficiently. (Hutchinson and Gallant 1999).

The recommended grid cell size is a compromising resolution, usually set as the intermediate number between the coarsest and finest resolutions. It can be computed taking the inherent data properties into account, using principles from the general statistics, information theory, and signal processing, and equations to estimate probability density functions (Hengl 2006). A smaller cell size allows capturing more and smaller features in greater accuracy at the cost of larger raster datasets with extensive data storage space requirements, which in turn often lead to longer processing times.

From the stereo-metric processing of the Ikonos Stereo Imagery, the vertical spatial accuracy of the dataset is one meter verified for the immediate surroundings of the minaret where excellent acquisition conditions occur. However, the very steep inclination of the terrain leads to areas with sparse point density, especially in the shadowed parts. To achieve the best results, these areas were treated with special attention through manual operations. Here the self-programmed implementation of the interpolation algorithm (Franklin 2000) provided far better results than the standard functions of the Leica Software and allowed for overall smooth elevation data leading to acceptable results for 90% of the covered area.

Considering the processing power of the available hardware and software[3], the chosen cell grid of the final DEM has a horizontal resolution of 5m

3 The processing equipment consisted of desktop computer AMD Phenom II X6 3.0GHz 6-core system with 16GB RAM, NVIDIA Quadro 2000 3D graphics card + NVIDIA 3D stereo glasses.

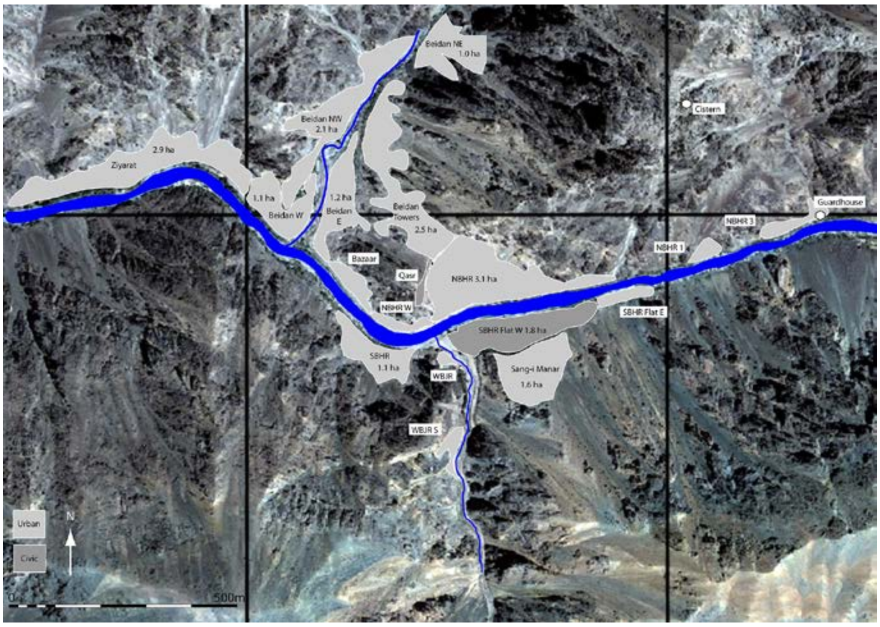

Figure 7. Mapping of the extent of the archaeological remains after field survey (Thomas 2012:340).

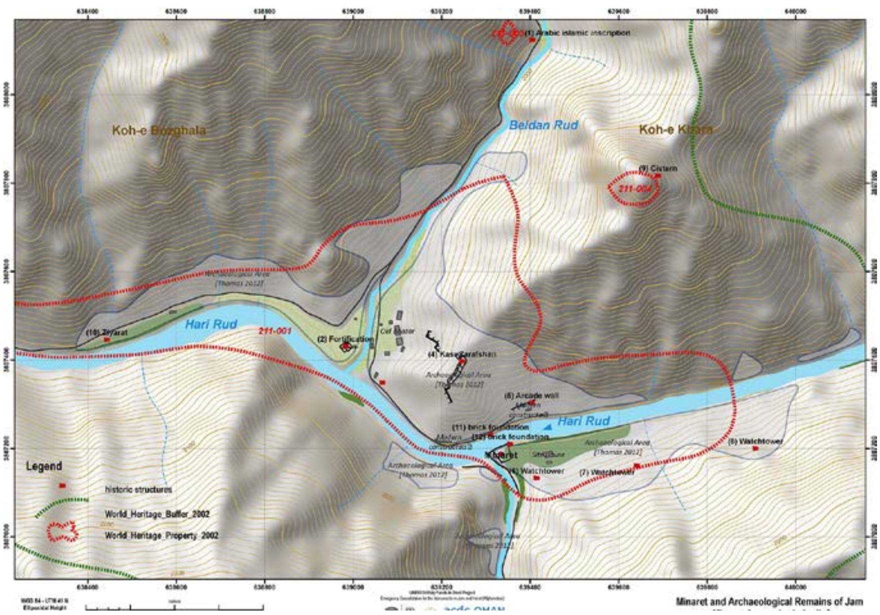

Figure 8. Ortho-rectified and shaded relief map with the central area of the Minaret of Jam and its archaeological remains – note the outline of the red property boundary copied from the nomination map.

since very high-resolution digital elevation models with smaller grid cells only produce slightly better results in terrain analysis tasks (Warren et al. 2004). The DEM covers an area of about 5.5km x 7.3km with elevation values ranging from 1878m to 2766m and approximately 1.600.000 pixels in total. The DEM also proved very suitable for subsequent use in hydrological applications to evaluate dangers arising from the river system, to calculate flood occurrences, and to assess the requirements for river protection measures (Schüttrumpf and Cofalla 2014). The elevation values correspond to WGS84-ellipsoid, which is identical to the GPS coordinate system. The geo-referencing of the satellite imagery is based on orbital parameters delivered as Rational Polynomial Coefficients (RPC) by the provider as part of the metadata of the satellite image and processed within the Leica Photogrammetry Suite. Several points at the UNESCO project house (100m east of the minaret) have been used because these structures could be precisely identified in the satellite imagery and were also measured during the field survey and included in the field survey data.

Considering the scale and functional requirements relative to digital terrain modelling (Weibel

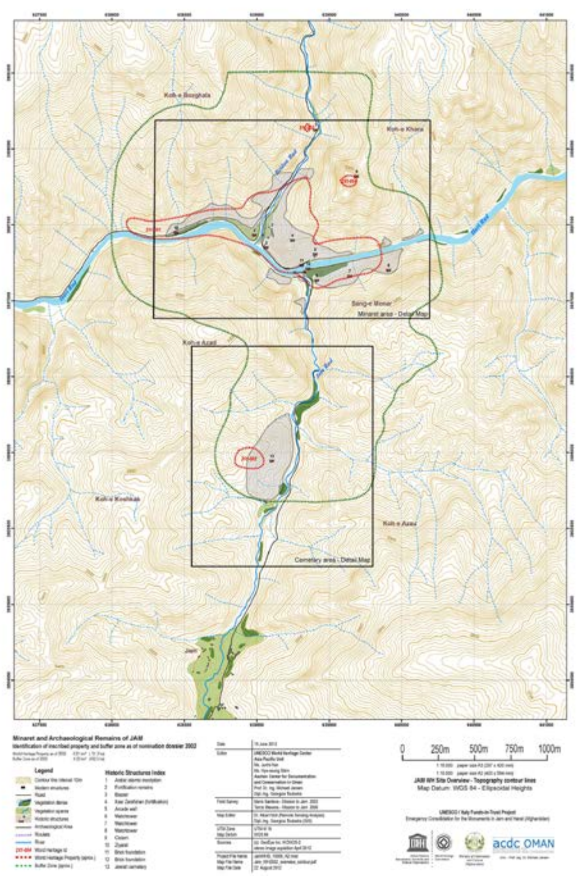

Figure 9. Delineation of inscribed World Heritage property and buffer zone as indicated in the nomination of 2002, projected onto the new topographic map with contour lines.

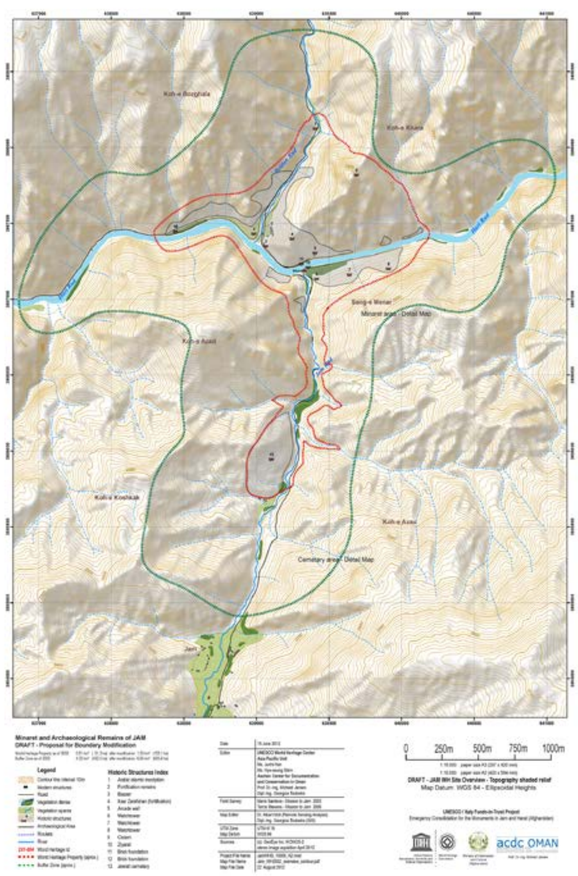

Figure 10. Proposal for minor boundary modification for the outline of the boundary of the property to the extent of the archaeological remains and adjusting the buffer zone based on the new map with shaded relief topography.

and Heller 1991) for the complete area, contour lines with 10m spacing are derived for further cartographic use (see Figure 5– right). This is done mainly by an automatic process and corrected by manual inspection via stereoscopic viewing, as mentioned above. The acquired two very high-resolution satellite images (WorldView-2) were projected onto the processed DEM to generate a geometrically correct orthoimage of the area, which can be used to derive high precision map information (one example see Figure 6). Several maps with scales ranging from 1:500 to 1:50.000 were set up and computed with ESRI ArcGIS 8.3 software.

Both the Ikonos and WorldView-2 satellite images consist of a colour-composite (colour and infrared channel) with 4m (Ikonos) and 2m (WV-2) resolution and a panchromatic (black/white) image with 1.0m (Ikonos) and 0.5m (WV-2) resolution. Pan-sharpening allows using the high resolution of the panchromatic image also for the colour image. By this method, the resolution of the panchromatic image is transformed and merged with the coarser colour-composite image to produce a final colour image with 1.0m per pixel resolution from the Ikonos image set and 0.5m per pixel resolution from the WV-2 image set, respectively.

As two high-resolution WorldView-2 scenes from different acquisition dates have been used, they have to be adjusted to each other to reduce brightness and colour differences and finally to be stitched together to a single scene. By coincidence, the overlapping of the two images was precisely the area around the minaret. Although from different dates, they prove useful to enhance the visual resolution of the scene. The transition between both images is hardly visible, besides a change in the colour of the Hari Rud due to different sediment content and river flow velocity in March and April (see Figure 6).

It has to be clearly stated that the absolute positional accuracy of all datasets (DEM, orthophoto, maps) relies on the quality of the measured points during the 2002/2006 campaign. Any potential shift due to GPS/measurement errors of these points leads to the same shift in all datasets. Relative accuracy, the position of all objects and the terrain to each other, is marginally affected by a potential bias in the measured dataset. Relative horizontal accuracy is 1m evaluated and validated for the surrounding area of the minaret based on the terrestrial range data from the field campaigns. Altogether 2000 points from the 2002 campaign and 1700 points from the 2006 campaign were used to achieve significantly higher geocoding accuracy.

These maps contain elevation information, contour lines, a complete stream network, imagery and objects in different combinations. From the satellite images also built structures can be identified and inserted into the map, which now serves as the basis for the local site management. The method proved to be applicable and very useful, especially under conditions where access to cultural properties is limited due to security reasons.

The Extent of Archaeological Remains

UNESCO initiated limited archaeological explorations in order to receive the information requested by the Afghan authorities concerning possible threats from a motorway project at that time planned to pass the minaret. A second exploration campaign in 2005 by Cambridge University could collect further information to determine the extent of the World Heritage property better. From these scientific explorations (Thomas 2012; Thomas et al. 2004) so far, it is possible to define the extent of the archaeological remains at the site of Jam (Figure 7).

The information at that time was mapped to a high-resolution satellite image, without having the possibility to correct this image geometrically, leading to a considerable displacement of the archaeological areas with the real topographic setting. The archaeological information was therefore transferred to the ortho-rectified map, and the extent of the "core and buffer zone" from the initial nomination dossier was projected onto the real topography (Figure 8). By this procedure, it became clear, that the boundaries of the World Heritage property require a modification to engulf the known areas of archaeological significance correctly.

Conclusions Regarding the World Heritage Property and Buffer Zone

Sufficient detailed information on the topography and the structural remains of the archaeological site of Jam and its surrounding area are now available to correct the shortcomings of the initial site map of the 2002 nomination dossier. The boundary information in the nomination file and the interpretations regarding the extent of archaeological remains were projected onto the new topographic information created from the stereo satellite images. The results are depicted in the new site map for the World Heritage Site of Jam (Figure 9-left).

The superposition of all information demonstrates that the delineation of the inscribed World Heritage property only partly is covering the extent of the archaeological remains in reality. The boundaries are running across steep hills regardless of topographic conditions. The area identified as a cemetery with Hebrew inscriptions located in the south was marked too small in the initial map. The real extent of the cemetery is considerably larger and almost intersects with the delineation of the initial buffer zone.

The authors, therefore, propose the adjustment to the boundaries of the World Heritage property to be considered on behalf of the State party. The national authorities should formally submit a request for a minor modification to the boundaries to the World Heritage Committee for approval as stated in Paragraph 164 and Annex 11 of the Operational Guidelines for the implementation of the World Heritage Convention (UNESCO World Heritage Center 2017). This request is justified considering the identified real-world location of the archaeological remains within the topography and also the essential views onto the monument along the steep valleys and mountain ridges. The authors recommend using the new topographic map and the proposed adjustment to the boundaries of the World Heritage property and the buffer zone as depicted in the shown map (Figure 10 right) to substitute the initial map in the nomination file of 2002.

Acknowledgements

Professor Michael Jansen died on 13. July 2022 while on duty as UNESCO expert at the World Her-

itage property of Samarkand – Crossroad of Cultures. He was a renowned scholar in the field of cultural heritage preservation, and his contributions to the international safeguarding campaign for the preservation of Afghanistan's cultural heritage are widely acknowledged. His tireless efforts and dedication to the cause have left an indelible mark on the field.

References

Ball, W 1982 *Archaeological Gazetteer of Afghanistan. Catalogue des Sites Archéologiques d'Afghanistan. Avec la collaboration de J.-C. Gardin*. Paris: Edition Recherche sur les civilisations.

Borgia, A 2002 *Preliminary geological hazard and foundations assessment at the Minaret of Jam, Afghanistan*. UNESCO technical report.

Comer, D C and Harrower, M J (eds.) 2013 *Mapping archaeological landscapes from space*. New York: Springer.

Franklin, W R 2000 Applications of Analytical Cartography, *Cartography and Geographic Information Science*, 27(3): 225–238. DOI: https://doi.org/10.1559/152304000783547812

Fraser, C, Baltsavias, E and Gruen, A 2002 Processing of Ikonos imagery for submetre 3D positioning and building extraction, *ISPRS Journal of Photogrammetry and Remote Sensing,* 56(3): 177–194. DOI: https://doi.org/10.1016/S0924-2716(02)00045-X

Fraser, C S and Hanley, H B 2003 Bias compensation in rational functions for Ikonos satellite imagery, *Photogrammetric Engineering & Remote Sensing*, 1: 53-57(5). DOI: https://doi.org/10.14358/PERS.69.1.53

Fraser, C and Yamakawa, T 2003 Applicability of the affine model for Ikonos image orientation over mountainous terrain. In: Heipke, C., Jacobsen, K., and Schroeder, M. (eds.) *High resolution mapping from space. Proceedings of the 2003 ISPRS-EARSeL joint workshop on "High-Resolution Mapping from Space"*. Hannover: Institute of Photogrammetry and Geoinformation., pp. 6–8.

Grodecki, J 2001 IKONOS Stereo Feature Extraction - RPC Approach, *American Society for Photogrammetry and Remote Sensing (ed.) Gateway to the new millenium Proceedings of ASPRS 2001 Conference, St. Louis,* April 23-27, 2001, 8.

Grodecki, J and Dial, G 2001 IKONOS geometric accuracy. *Proceedings of joint workshop of ISPRS working groups I/2, I/5 and IV/7 on high resolution mapping from space.* pp. 19–21. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.476.5767&rep=rep1&type=pdf [Last accessed 26 August 2018].

Gruen, A, Remondino, F and Zhang, L 2005 3D Modeling and visualization of Cultural Heritage sites from high-resolution satellite imagery. In: Marcal, A. (ed.) *Global developments in environmental earth observation from space. Proceedings of the 25th symposium of the European Association of Remote sensing Laboratories.* Porto: Millpress, pp. 6–11.

Han, J (ed) 2015 *From the past and for the future: Safeguarding the Cultural Heritage of Afghanistan – Jam and Herat*. Paris: UNESCO.

Hengl, T 2006 Finding the right pixel size, *Computers & Geosciences,* 32(9): 1283–1298. DOI: https://doi.org/10.1016/j.cageo.2005.11.008

Herberg, W and Davary, G D 1976 Topographische Feldarbeiten in Ghor. Bericht über Forschungsarbeiten zum Problem Jam-Ferozkoh, *Afghanistan Journal*, 3(2): 57–69.

Hutchinson, M F and Gallant, J C 1999 Representation of terrain. In: Longley, P.A., Goodchild, M., Maguire, D.J., and Rhind, D.W. (eds.) *Geographical information systems: principles and technical issues*. New York: Wiley. pp. 105–124.

ICC 2003 *Recommendations of the First Plenary Session of the International Coordination Committee for the Safeguarding of Afghanistan's Cultural Heritage (ICC).*

ICOMOS 2002 *Advisory Body Evaluation: Minaret of Jam (Afghanistan),* No 211. Available at http://whc.unesco.org/archive/advisory_body_evaluation/211rev.pdf [Last accessed 26 August 2018].

Kraus, K and Harley, I 2007 *Photogrammetry: geometry from images and laser scans*. (2. ed.) Berlin: de Gruyter.

Maricq, A and Wiet, G 1959 Le minaret de Djam: la découverte de la capitale des sultans Ghurides (XIIe–XIIIe siècles). *MDAFA-Mémoires de la Délégation Archéologique Française en Afghanistan 16*. Paris: Klincksieck.

Martin, O and Piatti, G 2009 World Heritage and Buffer Zones. *World Heritage papers 25*. Paris: UNESCO .

Menon, A, Lai, C G and Macchi, G 2004 Seismic hazard assessment of the historical site of Jam in Afghanistan and stability analysis of the minaret, *Journal of*

Earthquake Engineering, 8(1): 251–294. DOI: https://doi.org/10.1080/13632460409350527

Pinder-Wilson, R 2001 Ghaznavid and Ghurid Minarets, *Iran Journal of the British Institute of Persian Studies*, 39: 155–186.

Santana Quintero, M and Stevens, T 2002 *Metric survey tools in recording: Mussalah complex Herat and Minaret Jam (October - November 2002)*. UNESCO technical report

Schüttrumpf, H and Cofalla, C 2014 Identification of river and flood protection measures for the world cultural heritage Jam in Afghanistan. In: Toubekis, G, Jansen, M, Han, J, and Shim, H (eds.) *Minaret of Jam. Safeguarding of a UNESCO World Heritage property.* Aachen: Aachen Center for Documentation and Conservation (acdc). pp. 39–46.

Sourdel-Thomine, J 2004 Le minaret Ghouride de Jām: un chef d'œuvre du XIIe siècle. *Mémoires de l'Académie des Inscriptions et Belles-Lettres 29*. Paris: De Boccard.

Stevens, T 2006 *Emergency Consolidation and Restoration of Monuments in Herat and Jam - UNESCO mission 22 July - 04 August 2006*. UNESCO technical report.

Thomas, D 2012 *The ebb and flow of an empire: the Ghūrid polity of central Afghanistan in the twelfth and thirteenth centuries*. Melbourne:La Trobe University.

Thomas, D C, Deckers, K, Hald, M M, Holmes, M, Madella, M and White, K 2006 Environmental evidence from the minaret of Jam archaeological project, Afghanistan, *Iran Journal of the British Institute of Persian Studies*, 44(1): 253–276. DOI: https://doi.org/10.1080/05786967.2006.11834689.

Thomas, D, Pastori, G, Cucco, I and Giunta, R 2004 Excavations at Jam, Afghanistan, *East and West*, 54(1/4): 87–119. DOI: https://doi.org/10.2307/29757608.

Toubekis, G, Jansen, M, Han, J and Shim, H (eds.) 2014 *Minaret of Jam. Safeguarding of a UNESCO World Heritage property*. Aachen: Aachen Center for Documentation and Conservation (acdc).

UNESCO 1972 *Convention Concerning the Protection of the World Cultural and Natural Heritage*.

UNESCO World Heritage Centre 2002 *Minaret and Archaeological Remains of Jam - Map. UNESCO World Heritage Centre*. Available at https://whc.unesco.org/en/list/211/ [Last accessed 2 September 2018].

UNESCO World Heritage Centre 2017 *The Operational Guidelines for the Implementation of the World Heritage Convention.* Available at http://whc.unesco.org/en/guidelines/ [Last accessed 2 September 2018].

Warren, S D, Hohmann, M G, Auerswald, K and Mitasova, H 2004 An evaluation of methods to determine slope using digital elevation data, *CATENA*, 58(3): 215–233. DOI: https://doi.org/10.1016/j.catena.2004.05.001.

Weibel, R and Heller, M 1991 Digital terrain modelling. In: Maguire, D.J., Goodchild, M. and Rhind, D.W. (eds.) *Geographical Information Systems: Principles and Applications*. New York: Longman Harlow/Wiley. pp. 269–297.

Zhang, L and Gruen, A 2006 Multi-image matching for DSM generation from IKONOS imagery, *ISPRS Journal of Photogrammetry and Remote Sensing*, 60(3): 195–211. DOI: https://doi.org/10.1016/j.isprsjprs.2006.01.001.

Patrick Cuthbertson & Peny Tsakanikou
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Challenges in Palaeolithic Spatial Archaeology: Two Eurasian Case Studies

Patrick Cuthbertson
Centre for the Archaeology of Human Origins (CAHO), Department of Archaeology, University of Southampton
patrick.a.cuthbertson@gmail.com

Peny Tsakanikou
Centre for Archaeology of Human Origins (CAHO), University of Southampton,
pt1g14@soton.ac.uk

Abstract

Palaeolithic applications of Geographic Information Systems (GIS) are increasingly common, however, theoretical discussion specifically addressing issues of Palaeolithic GIS is practically non-existent. In this paper, we argue that such a discussion is necessary because Palaeolithic applications of GIS are subject to unique conditions and challenges. We specifically highlight the issues of data quality, the vast spatio-temporal scale, and the difficulty of interpreting patterns of hominin behaviour in relation to the first two conditions. We illustrate and discuss these problems as they related to our own doctoral projects, studying Lower Palaeolithic dispersal and occupation first in Central Asia and then in the Aegean (NE Mediterranean). We discuss the methodological approaches we took in tackling the major topics of our study regions, and identify several commonalities in the difficulties we faced implementing them. In concluding, we define three 'challenges' of Palaeolithic GIS, and three 'temptations' arising out of those challenges.

Keywords: Palaeolithic, GIS, dispersal, landscape, affordances, accessibility

Introduction

Palaeolithic researchers today are using Geographic Information Systems (GIS) at many different levels of research, such as in site prediction, prospection, and survey (e.g Cuthbertson et al. 2021; Jennings et al. 2015; Sauer, Stott and Riede 2018, in combination with remote sensing see Breeze et al. 2015, 2016, 2017), intra-site spatial analysis (e.g. Coil et al. 2020; García-Moreno et al. 2021; Neruda 2017), and in reconstructing palaeolandscapes, resources, and dispersals (e.g. Field and Lahr 2005; Field, Petraglia and Lahr 2007; Holmes 2007; Li et al. 2019; Tsakanikou, Galanidou and Sakellariou 2020). However, there is very little explicit discussion on what that usage means for the discipline, in what ways that usage may be unique in comparison to later periods, and how that usage might be directed into the future. An example of what such a discussion would look like can be seen in an informative paper published by Anemone et al. (2011). The paper reviews a number of applications of GIS in palaeoanthropology, showing how palaeoanthropological questions can be addressed using geospatial analyses, but also how spatial analysis itself can provide innovations to the framework of palaeoanthropological research. Palaeolithic archaeology has not yet had a similar 'watershed' moment of self-reflection centred on Palaeolithic applications of GIS.

Common challenges that the present authors faced during our doctoral projects highlight some of these issues as they relate to applications of GIS in the Palaeolithic. We both tackled broadscale dispersal topics for our projects, and discovered in discussion that we had many similarities in the challenges we were encountering. We wondered if these were broader issues faced by other practitioners, and were surprised when we found little to no body of literature addressing them.

This was the starting point for us organising the

CAA2018 session 'Palaeo-GIS', because we wanted to bring together practitioners of Palaeolithic GIS to get an assessment of the 'state of the art', and to gauge interest in a theoretical discussion grounded in Palaeolithic applications. We also wanted to see if ideas for future development of the sub-discipline could be discussed, and if we could propose some of our own. The reception of the session was very positive, and underlined the need for such a discussion to take place.

Although Palaeolithic applications of GIS can be broadly divided into fieldwork-focused projects and desk-based analyses, many of the researchers doing Palaeolithic GIS are also Palaeolithic fieldworkers performing data collection, which is not always the case in other areas of archaeological GIS. This practical focus suggests that currently innovation in Palaeolithic GIS emerges primarily from technological innovation (such as the use of drones, remote sensing data, etc.) rather than innovations in Palaeolithic spatial theory. These factors heavily favour a view of prospection and predictive mapping as the primary aim of GIS in Palaeolithic research, while later periods have arguably achieved a wider range of theoretical and methodological concerns decades earlier (for a variety of examples see Lock 2000; Lock and Stančič 1995).

It is our contention that Palaeolithic applications of GIS deal with unique issues in comparison with GIS applications of other periods, and that these issues are chiefly caused by three main factors;

Firstly, unique uncertainties are introduced by the fragmentary nature of the record and the unevenness of the coverage. Coping with the incompleteness of the data available requires serious consideration of how certain spatial analyses might be applied, whether certain analyses are valid at all for such datasets, and requires careful consideration of the validity of reconstructing datasets.

Secondly, the vast spatio-temporal scales that Palaeolithic contexts require for their study is something that Palaeolithic research shares with no other period of archaeological study. The struggle of implementing concepts such as deep time and continental dispersal within spatial analysis is not something that later period archaeology deals with to the same extent. However, it is a struggle that Palaeolithic researchers share with geologists, and much value may lie in an approach combining concepts from both in spatial analysis.

Thirdly, both the spatio-temporal scale and the fragmentary nature of the dataset affect the resolution of questions and behavioural interpretations (adaptive and evolutionary) that are possible in Palaeolithic applications of GIS.

There is a substantial lack of theoretical consideration supporting Palaeolithic applications of GIS, and the present authors contend that the development of such a body of research is doubly necessary to address the unique issues of such applications, not least of all those three main factors outlined above.

Although intra-site spatial analysis is also a very common application for GIS in Palaeolithic periods, our focus here is on landscape-level applications. Using two case studies from the Lower Palaeolithic peopling of Eurasia, firstly in the area of Central Asia and secondly in the area of the Aegean, we will illustrate the problems we faced in the course of our projects, and our thoughts on possible future directions for Palaeolithic applications of GIS.

Lower Palaeolithic Central Asia and the Northern Dispersal Route

Central Asia represents a challenging region for discussions of Lower Palaeolithic dispersal in Asia. The region is bracketed by significantly older dates to the west and east. The oldest widely-accepted securely-dated sites currently known in Asia are Dmanisi (Georgia, 1.8 Mya, Ferring et al. 2011) and Shangchen (China 2.12 Mya, Zhu et al. 2018). However, the oldest dated site in Central Asia is no older than about 1 Mya (Ranov and Dodonov 2003). This is notable because Central Asia lies on roughly the same latitude as these older sites, and is a known migration route in later periods, the eponymous silk road. Substantial mountainous and desert zones are also likely to have constrained hominin movement through the region.

The primary causes of this pattern could be taphonomic, a result of investigation bias, or a result of Pleistocene environmental dynamics. This question was investigated by reconstructing elements of the early Pleistocene environment in Central Asia, and using versions of the concept of 'affordances' and accessibility analysis to interrogate that environmental dataset. Three challenges in particular presented themselves relating to the three main factors highlighted earlier;

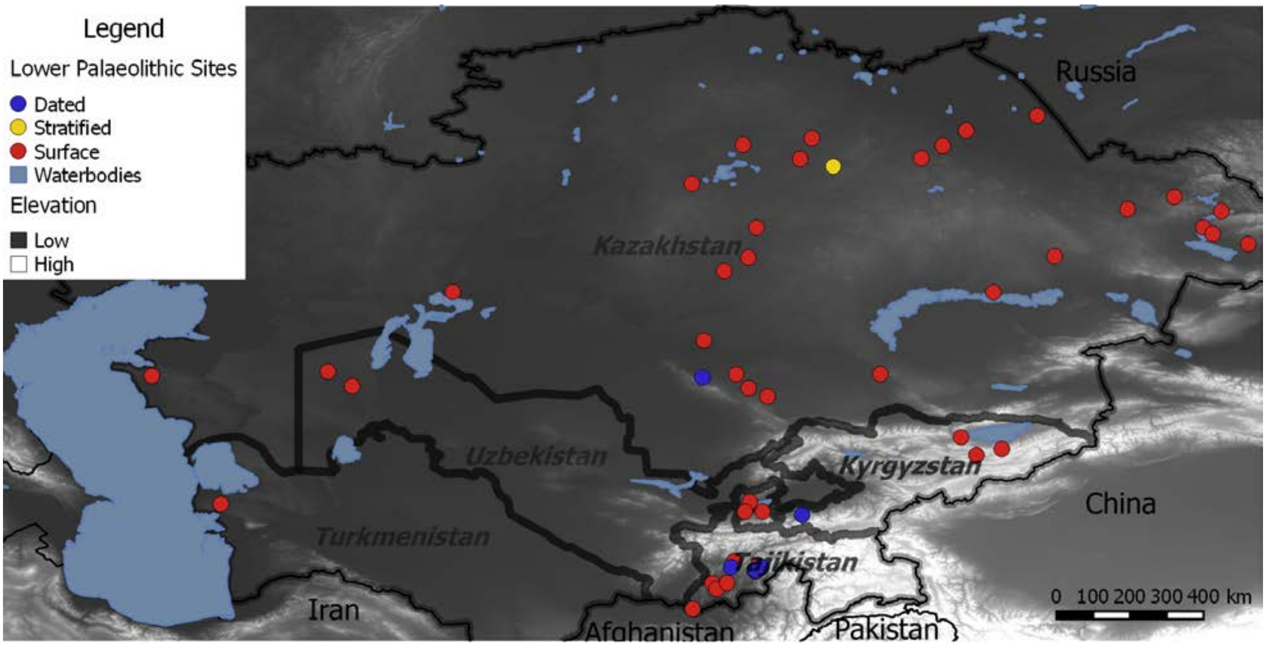

Figure 1. The study region of Central Asia includes the modern boundaries of Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan. The heavily clustered nature of the few Lower Palaeolithic dated sites in the study region provided a substantial challenge for analysis. This map includes data provided by M. Glantz, T. Beeton, S. Temirbekov, & B. Viola. Global Administrative Areas (GADM), developed by Robert Hijmans and colleagues. Made with Natural Earth. Free vector and raster map data @ naturalearthdata.com. Shuttle Radar Topography Mission (SRTM) Version 4, Jarvis A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org. Map produced using QGIS 2.18.9.

1. How to deal with variability in preservation and data coverage, particularly because the region has not been extensively investigated previously and existing sites are heavily clustered (see Figure 1).

2. How to deal with a spatio-temporal scale that includes a time-range of almost 900 ky and a continental spatial extent.

3. How to model and interpret patterns of hominin behaviour from such datasets and at such scales.

Data Problems and Best Practice

In the course of this Central Asian Palaeolithic GIS project, two major issues related to data quality were noted early on;

Firstly, there was little certainty about the necessary quality of data and the minimum best practice for data-use. Although several Palaeolithic GIS applications exist in the literature as case studies, very few address data or quality requirements (but see Kamermans and Rensink 1999 for a rare example, and also see Brouwer Burg 2013; Spikins and Engen 2010 for two Mesolithic examples with relevance to Palaeolithic applications).

Secondly, there is a lack of discussion about methodological solutions to uncertainty in the record, and best practice surrounding this issue. A lack of understanding about what constitutes best practice means that students have little support in planning their own GIS projects tackling Palaeolithic research questions. Furthermore, the sub-discipline as a whole lacks clarity for assessing such projects.

A lack of Lower Palaeolithic sites in Central Asia presented a substantial challenge, as only five dated sites are reported, and the dating quality varies between them (see Figure 1). It remains challenging to address this uncertainty in analysis without making unnecessary assumptions, such as introducing arbitrary weighting, or in a way that is not purely a visual representation. Furthermore, all of these dated sites are located in the south-east of a very large study region. This clustering required careful consideration of the analytical methods used and what kinds of assumptions these methods made. A common solution has been simply to ignore dating uncertainty or temporal gaps of thousands of years, and treat sites as de facto contemporaneous, especially in more derived analyses that may be reliant on site location such as least-cost analyses.

The difficulty of acquiring data with coverage over Palaeolithic time periods raises a further challenge surrounding the use of related relevant datasets. The use of a relevant proxy dataset can be a way of overcoming a dearth of data for a chosen spatio-temporal bracket, but exactly how good a proxy dataset should be, and what justifies its use, is still largely undefined as an issue of best practice. This became a crucial question in the use of climate data in the present project for building an affordance surface of Central Asia.

Although numerous sections and cores across the study region contribute a wealth of environmental information for the Lower-Middle Pleistocene, data with a spatial extent (such as that produced by climate simulation models) are rare to non-existent. Although palynological data from a large number of sites was available with reasonable temporal coverage, these are heavily concentrated in the loessic regions of the south and east, in much the same way as the archaeological sites are. Vertebrate remains that may also have helped reconstruct environment were also extremely limited for the timeframe in the study region, surviving poorly in the loess. We regarded these data as too meagre for even an ambitious and experimental modelling procedure. The WorldClim Last Interglacial climate models were the closest, freely available match for my own project (Otto-Bliesner et al. 2006), but only covered the very end of the time range considered. Therefore, it could not account for the numerous oscillations between glacial and interglacial conditions throughout the Lower-Middle Pleistocene, which are sure to have had a profound effect on the amenability of the environment for hominin occupation.

The solution arrived at was to average the monthly WorldClim data together to provide a yearly average for different climate variables, and to then normalise these surfaces to remove the absolute values of the Last Interglacial. Individual absolute estimates from environmental data within the time range were used to 'anchor' these patterns discursively, and provide an idea of the variability within glacial cycles. Literature-based arguments were used to support the idea that the relative patterning of these climate variables was likely to have been broadly preserved, even as the absolute values had certainly changed. More detailed consideration of environmental change could only be approached discursively in the literature review and in the interpretations of the results.

It is unclear in the current Palaeolithic GIS literature what constitutes 'best practice' for data challenges such as these. An explicitly theoretical discussion is not yet established for issues of data quality and best practice in Palaeolithic applications of GIS, and this represents a great omission, particularly felt by young researchers who are attempting to develop in this sub-discipline. It remains an issue that much palaeoclimate data is not available to Palaeolithic researchers in a way that is spatially meaningful to their analyses, and that the tools and best practice to address this are still poorly explored.

Spatio-Temporal Scale

We suggest that the wider spatio-temporal scale of Palaeolithic GIS is the source for much of the unique difficulties faced by researchers in this sub-discipline. Questions about best practice and theoretical approach are hard to transpose wholesale from later periods for just this reason.

There is good reason to expect that unique spatio-temporal factors affect Palaeolithic GIS. Palaeolithic archaeology has always been closer in theoretical and methodological basis to geology rather than to later period archaeology. The record is itself more akin to a geological one in its fragmentary nature and its material contexts. Inevitably, some forms of spatial analysis in later periods should be expected to relate differently to the Palaeolithic record, or may even be of little or no relevance to human behaviour at Palaeolithic scales at all.

For example, reconstructing river hydrology from contemporary topography is a standard form of spatial analysis for later periods of archaeology. Sometimes specific reasons exist why such analyses are not valid in later period case studies, but these reasons are further compounded by the spatio-temporal scale of the Palaeolithic. Despite this, the ubiquity of hydrological analysis in later periods has meant that this form of analysis has often been suggested to

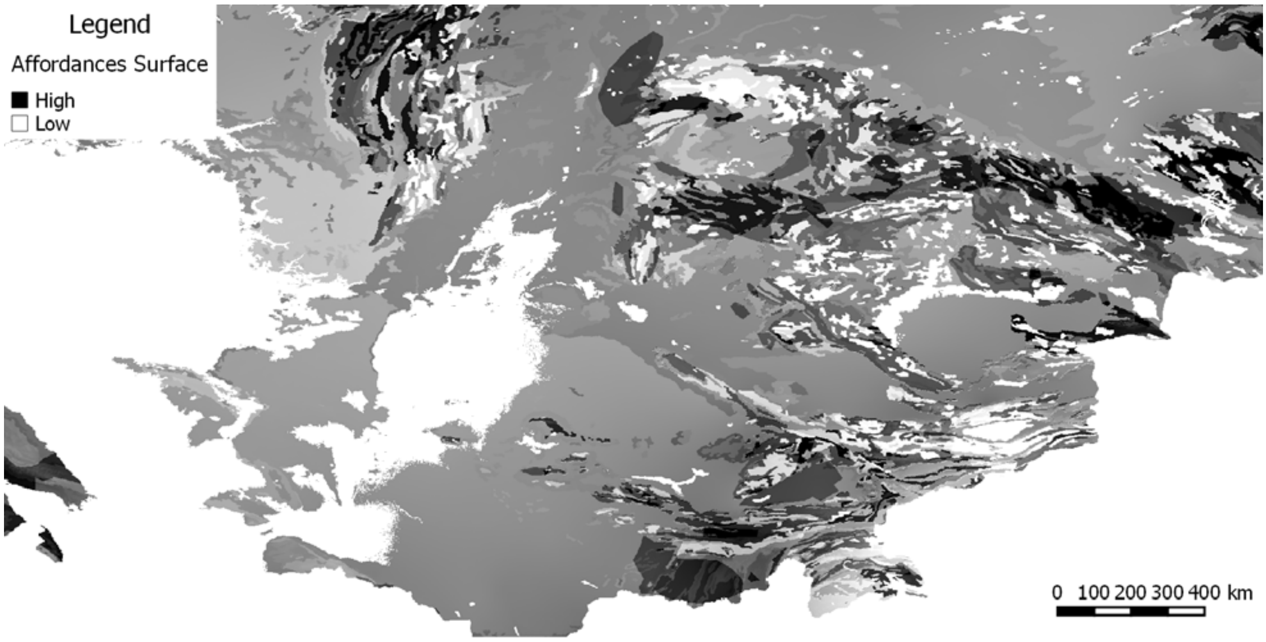

Figure 2. The affordances analysis combined a number of environmental attributes, including precipitation, groundwater potential, and raw material availability, to produce a 'hominin-centred' view of the landscape of Central Asia. Using datasets derived from WorldClim 1.4 temperature and precipitation derived from LIG palaeoclimate models, published by Otto-Bliesner et al. (2006) http://www.gadm.org/about and datasets derived from Generalized Geology of the Former Soviet Union (geo1ec). Published 1998 by the U.S. Geological Survey, Central Energy Resources Team and Dr. Thomas Ahlbrandt. https://certmapper.cr.usgs.gov/data/we/ofr97470e/spatial/shape/geo1ec.zip https://energy.cr.usgs.gov/oilgas/wep/. Map produced using QGIS 2.18.9.

one of the authors (P. Cuthbertson) for application to early Pleistocene Central Asia. This form of analysis was not attempted or credited for two main reasons;

Firstly, the majority of the dated sites in the study region come from loess sequences. These sequences have a non-trivial relationship with hydrology, as they often form where major rivers cut into loess deposits. Therefore, there is a clear non-behavioural reason for such sites to be located along major rivers, and therefore 'proximity to water' as represented by a modelled river network is worse than meaningless.

Secondly, even within historical times, the major rivers of Central Asia have been known anecdotally to change course after earthquakes (Hopkirk 1993: 160). This is compounded by the aeolian erosional and depositional processes active in the region, where dust storms have transported vast quantities of sediment from one side of Central Asia to the other. At a very broad spatio-temporal scale such as this, most of the depth of loess accumulation falls within the error range of the most common elevation datasets that can be used at this scale. In spite of this, the fact that the river systems have been known to change within this region within historical times highlights the folly of attempting such an analysis, and in assuming that such features derived from modern digital elevation models would prove meaningful for Pleistocene behaviour.

The challenges of the spatio-temporal scale are at the root of the difficulties of modelling human behaviour in these contexts. Exactly what forms of analysis are valid for examining human behaviour at this scale, and how to interpret the results of those analyses, constitutes an additional challenge in and of itself.

Interpreting Behaviour: The Role of Environment versus Mobility and Access

Related to the challenges engendered by the spatio-temporal scale of Palaeolithic GIS, is the issue of how researchers interpret hominin behaviour at these scales. A specific example of such a problem that needs consideration is the issue of the role of the environment in determining hominin behaviour.

Where research in later periods might be criticised for overt environmental determinism (ED) (Gaffney

& van Leusen 1995), this debate has to be uniquely considered for the Palaeolithic. It must be assumed that many of past peoples' decisions would have been conditioned by the environment. For hominin ancestors this may have been even more so the case, due to their limited behavioural and technological adaptive buffers against environmental change compared to later periods. Considering their actions to be heavily determined by the environment may in fact provide the most parsimonious model for hominin ancestors. Therefore, any role that hominin agency should have within our models is not entirely clear.

The concept of affordances in the present project focused on Central Asia was based on Gibson's (1986: 127) definition, and was primarily driven by environmental data, such as geology, hydrology, precipitation, and temperature (see Figure 2). The analysis therefore had to make certain assumptions about how hominins identify and use resources in the landscape, and how this might manifest behaviourally. In order to avoid an overly environmentally deterministic methodology, any environmental data included within this analysis was specifically justified with reference to known parameters of hominin behaviour within the literature. Although this does not provide an absolutely concrete solution, it is at least an explicitly self-reflective framework for the use of environmental data to model hominin behaviour. Other possible assumptions of hominin behaviour exist, and could provide alternative parameters for models.

Movement and mobility generally, and the specific methodologies used with some success in later periods such as least-cost pathways and site catchment analyses (see Herzog 2020 for a recent summary), also become ambiguous at Palaeolithic spatio-temporal scales. For instance, it is unclear how a least-cost pathway analysis relates to a multi-generational timescale, or at what spatio-temporal scales increasing topographic cost can seriously be considered an obstacle either to access into or knowledge of an area. This is especially important, because sites that are considered broadly contemporary in the Palaeolithic may have dates with extremely large error-ranges versus those of later periods, and connectivity between them cannot be considered meaningful a priori. At worst, least-cost analyses are uncritically assuming that location is far more behaviourally meaningful than taphonomic factors of differential survival may suggest. In a similar way, although site catchment analyses are informative, they tell us foremost about the arbitrariness of a constrained site-centred focus. They reveal little about broader patterns of hominin-landscape interaction away from 'sites', which we must assume would characterise a continuous behavioural space like the Palaeoscape (à la Foley 1981).

The present project preferred a form of cost 'accessibility' analysis that used cost distance to investigate hominin dispersal into and through Central Asia from its most likely earliest entry point along the southern border. Accessibility analysis often refers to a form of network analysis (Conolly and Lake 2006: 241), usually applied in an urban setting. However, the current implementation used cost distance rasters drawing on the approach of Llobera, Fábrega-Álvarez and Parcero-Oubiña (2011), and originating from points on the southern border in an 'origin points to everywhere' style of analysis (see Figure 3). The analysis used the 'Cost Distance' tool in the ESRI ArcGIS 'Spatial Analyst' toolkit.

The results of the affordances mapping were used as the cost surface, meaning that the analysis rated movement through areas rich in predicted resources as less costly than movement through areas low in predicted resources. This drew on the approach of Whitley et al. (2010), where potential caloric yield of areas around sites on the Georgia Coastal Plain was used as a form of cost surface to examine issues of territory, dominance, and exchange. The goal of using affordances as a form of cost in the present project was to provide a model of mobility in Central Asia grounded primarily in subsistence activities and human action. An alternative would have been to incorporate topographic cost, however, although we must be fairly certain that substantial mountain chains in and around Central Asia would have provided obstacles to movement, exactly how and to what extent is not clear. Topography was specifically excluded from this analysis for this reason, as it is unclear how it relates to broad patterns of disperal and resource use in the landscape at these timescales.

Site location was also excluded, so the cost surfaces were calculated from 1000 points placed along the southern border of the study region (this represented the upper feasible limit for computa-

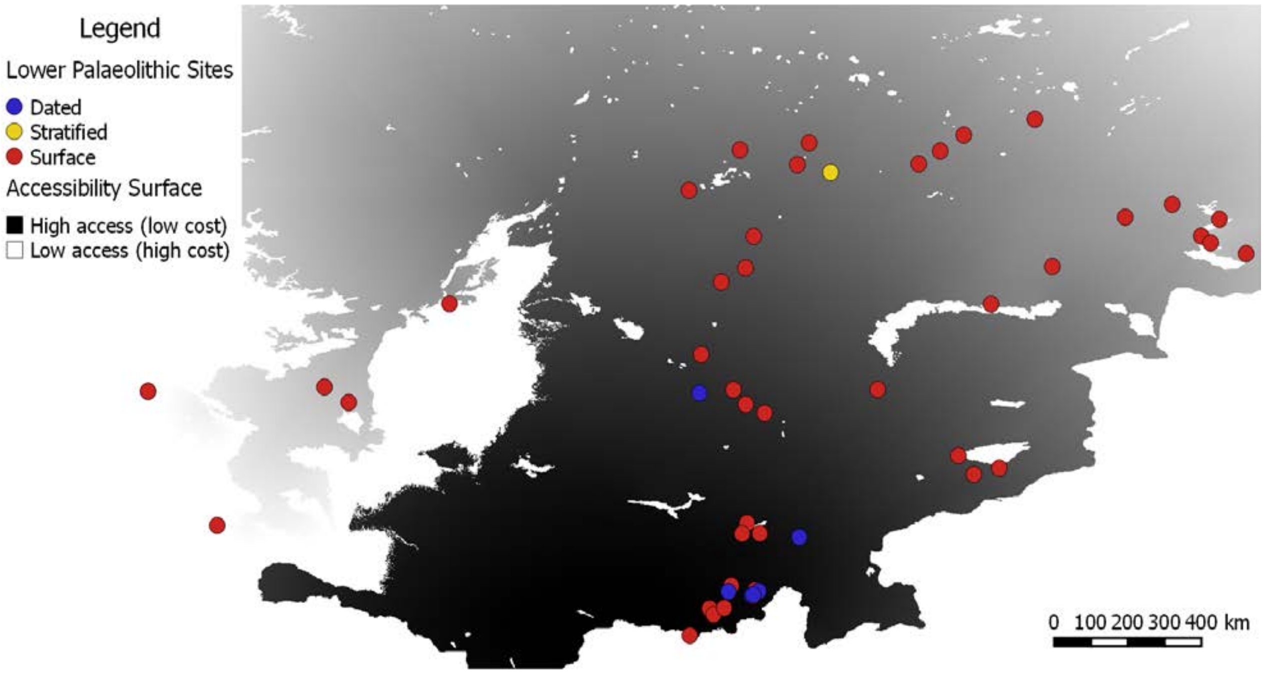

Figure 3. Accessibility was calculated as cost distance from the southern boundary which provides the most probable entry point into Central Asia during the Lower-Middle Pleistocene. It is assumed that the distribution of resources would play a large role in continental dispersal patterns, and that these results can be used to contextualise the positions of the existing sites. This map includes data provided by M. Glantz, T. Beeton, S. Temirbekov, & B. Viola. Map produced using QGIS 2.18.9.

tion). The 1000 resultant surfaces were combined together to provide a single surface that effectively represented the accessibility, costed through richness of environmental affordances, of every cell in the study region from the southern border points. In this way, it was possible to compare the accessibility of the different sites, without having to assume meaningful connectivity or contemporaneity between them.

In this Central Asian case study, we have highlighted problems the project faced due to issues of data coverage, and a lack of existing discipline-specific guidance for best practice in data requirements, the reconstruction of datasets, and the appropriate use of proxies. Issues of spatio-temporal scale in particular added a layer of difficulty to choosing appropriate datasets and analyses to address the research questions effectively. As Palaeolithic archaeologists, ultimately we are most concerned with understanding how those issues might map to the interpretation of hominin behaviour and the role of the environment at these scales. The solutions arrived at in regards to Central Asia were by no means perfect or definitive, but they were explicitly chosen, with alternatives considered and rejected.

The Aegean dry land hypothesis

Our second case study considers the Palaeolithic of the Aegean, which provided related but unique questions and solutions of its own. The Aegean is located at a crossroads between Africa, Europe and Asia, at the southernmost end of the Balkan Peninsula. The wider eastern and northeastern Mediterranean has been highlighted as a vital area during the Early and Middle Pleistocene, hosting refugia (Dennell, Martinón-Torres and Bermúdez de Castro 2011) and offering multiple and multidirectional dispersal routes (Kahlke et al. 2011; Spassov 2016). Despite the promising location, the Lower Palaeolithic evidence from the Aegean is sparse and the record is characterised by extensive spatio-temporal discontinuities and few securely dated sites. This low density of Lower Palaeolithic evidence is possibly the result of interpretation bias, reinforced by landscape dynamics (Tourloukis 2010). The Aegean is tectonically active, and this has an important impact on the availability and visibility of the Early and Middle Pleistocene material, favouring preservation and accessibility within specific geological contexts and under specific geomorphic circumstances.

The presence of hominins in the Aegean prior to 200 Kya was not previously securely documented, leaving this territory out of the discussion about the early colonisation of Europe. However, recent archaeological finds dated to around 400-500 Kya (Galanidou et al. 2013, 2016; Panagopoulou et al. 2015, 2018), and the re-examination of palaeoanthropological material attributed to the Middle or even the earlier Pleistocene (Harvati 2016), offer evidence for the reconsideration of the biogeographical role of the region. Furthermore, recent work on the submerged landscapes of the Aegean (Lykousis 2009; Sakellariou and Galanidou 2016, 2017) has revealed the existence of extensive exposed landmasses during the Middle and possibly Early Pleistocene. The current working hypothesis is that the Aegean was not a barrier during the Lower Palaeolithic, but instead an open terrestrial landscape, from at least MIS 10-12 (~480 Kya) until at least MIS 8 (~250 Kya).

Methodological Challenges

The main research question emerging is 'Could the exposed landscapes of the Aegean provide routes connecting Western Asia and Europe – an eastern passage to Western Europe (?) – and/or offer attractive lands for occupation during the Lower Palaeolithic?'

Several limitations pose serious methodological challenges;

1. In this project, the Aegean is treated as a terrestrial landscape. However, the environments and the topography of the now submerged landscapes are largely unknown.

2. The dynamic character of the tectonically active Aegean landscape, means that, the palaeotopography and the palaeogeography of the region suffered massive transformations throughout the Pleistocene and the Holocene.

3. Available datasets from the Aegean are problematic due to their scarce and discontinuous nature and due to temporal limitations, with available information covering efficiently only the last glacial cycle (last 130 Kya).

Assessing the Nature of the Palaeolandscape

The production of accurate and detailed reconstructions for the Aegean's deep past becomes extremely difficult due to the geotectonic history of the region and the ongoing geomorphic processes (framing the first two limitations outlined above).

The 'complex topography' concept offers a rigorous approach to overcome satisfactorily limitations relating to the nature of the past landscape because (a) it uses modern topography as a proxy (bypassing unavailability/lack of early data), and (b) it is applicable in (and suitable for) tectonically active areas (dealing with active processes). Bailey and King (2011; Bailey, Reynolds and King 2011; King and Bailey 2006) proposed the 'complex topography' hypothesis to suggest that tectonically active zones in East Africa favoured hominin occupation by providing diverse environments and natural pathways for movement.

In dynamic landscapes such as the Aegean, the topographic complexity can be measured by recording an index of landscape roughness using current elevation and bathymetry. Modern topographic complexity reflects to a certain extent the topographic complexity of the past landscape in areas with ongoing tectonic activity through the rejuvenation of the features produced by the geotectonic disturbance; landscape roughness – the measurement of irregularities on the surface morphology – is used as a proxy for identifying areas favourable to hominins.

Producing an index of landscape roughness for the Aegean highlights several specific areas as possible targets for further study (see Figure 4). High values of topographic roughness in the modern dynamic landscape would indicate areas with high topographic complexity in the past and over the same areas, and thus higher possibilities of recovering Lower Palaeolithic remains – if and where they were preserved. However, given that this work is based on modern elevation and bathymetry in a dynamic setting, where subsidence, uplifting, sedimentation, erosion, and sea-level fluctuations are taking place, what criteria should be followed to identify targets with the highest research potential? This concern led the preliminary identification of areas with high values of topographic complexity to be focused on parts of the Aegean where; (a) the main landscape features persist in time despite the action of

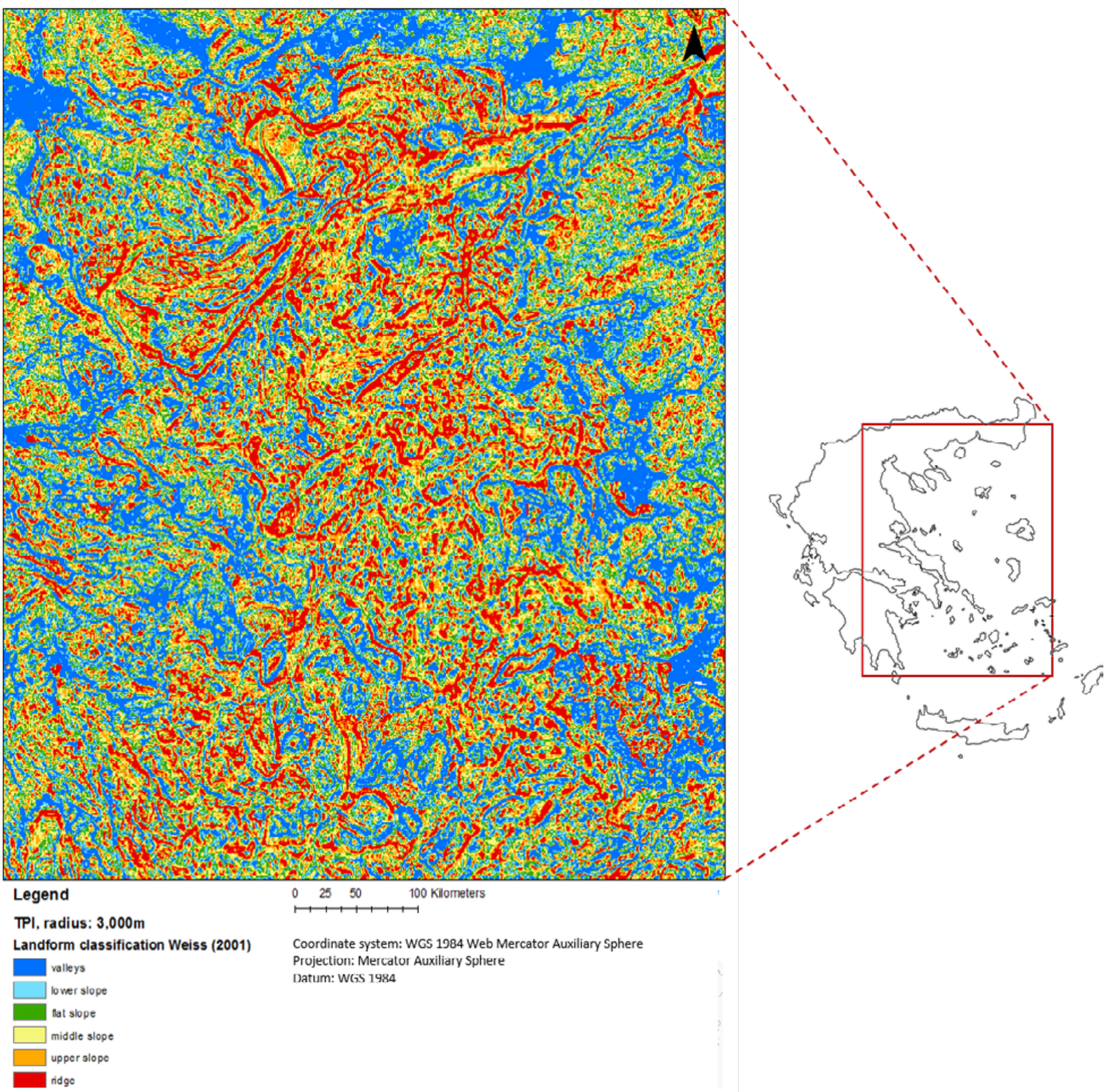

Figure 4. Roughness mapping on the Aegean, using the Topographic Position Index (3km radius). The landform classification follows the Weiss (2001) system. Terrain data: ASTER Global Digital Elevation Map, version 2 (ASTERGDEM V2) (30m resolution), available at NASA Land Processes Distributed Active Archive Center (LP DAAC). Bathymetric data: Eastern Mediterranean Bathymetric Map (2016) (250m resolution) by courtesy of the Hellenic Centre for Marine Research. The map is produced using ArcMap 10.4.

the geomorphic processes and where; (b) abundant and variable natural resources suggesting favourable environments for hominins have been documented through proxy data. Two areas meet these criteria: at the northern Aegean, along the continental self and the basinal structures of the North Aegean Trough, and at the south-central Aegean, over the Cycladic Plateau and along the Aegean Volcanic Arc (Tsakanikou and McNabb 2020).

Testing Hypotheses on Hominin Mobility and Survival over the Extended Terrestrial Aegean

The landscape roughness mapping sets the background to investigate further the nature of the Aegean terrain and its affordances (inspired by Gibson's (1986: 127) original definition). The research questions address two issues: (a) the traversability of the Aegean dry land and (b) the attractiveness of its habitats.

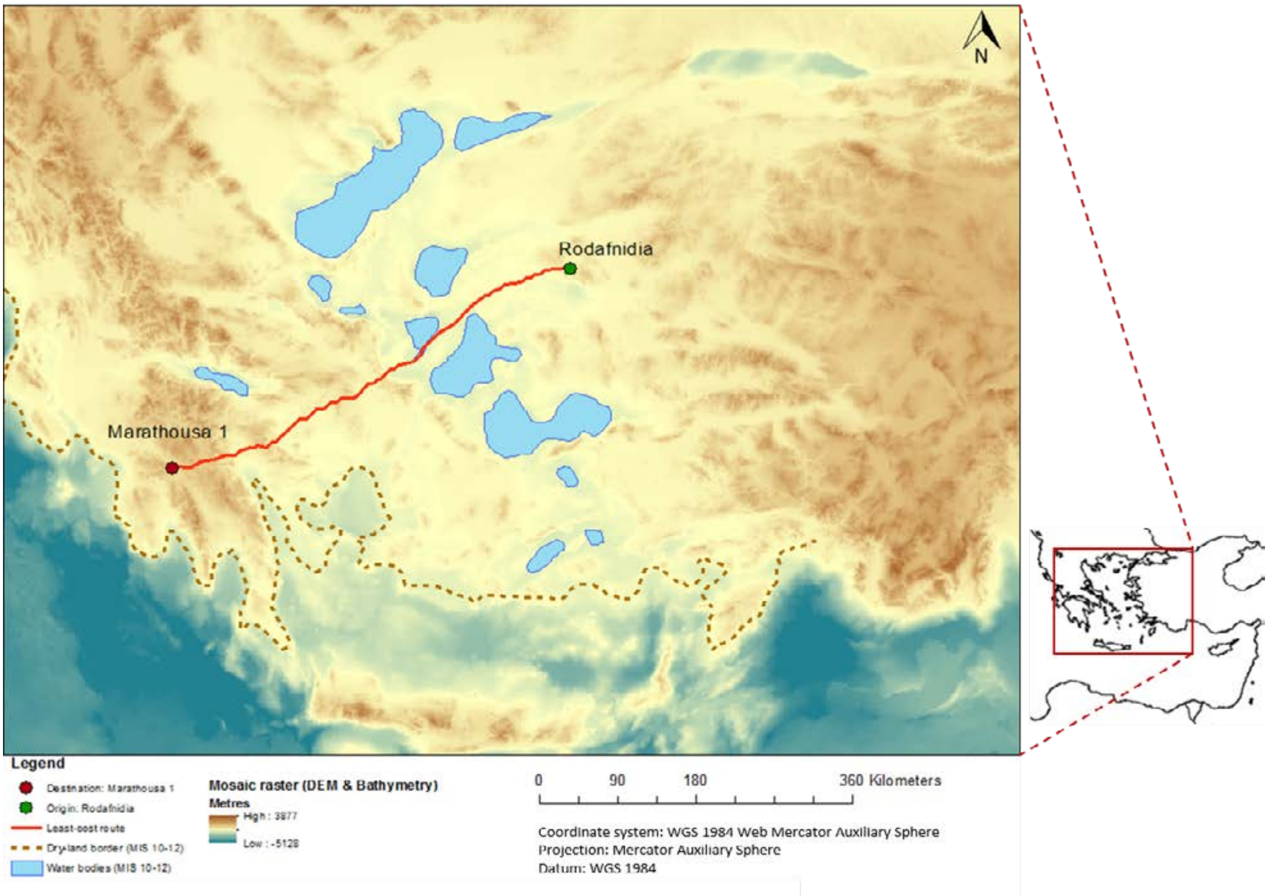

Figure 5. Least-cost route between Rodafnidia and Marathousa 1 sites. The location of the water bodies and the southernmost border of the Aegean exposed landscape during MIS 10-12 follow Lykousis (2009) palaeogeographical reconstruction. The background mosaic raster combines modern elevation and bathymetry. Terrain data: ASTER Global Digital Elevation Map, version 2 (ASTERGDEM V2) (30m resolution), available at NASA Land Processes Distributed Active Archive Center (LP DAAC). Bathymetric data: Eastern Mediterranean Bathymetric Map (2016) (250m resolution) by courtesy of the Hellenic Centre for Marine Research. The map is produced using ArcMap 10.4.

A least-cost route analysis approach was followed to test the potential of the Aegean as a traversable terrain. Although the least-cost route analysis has a gradually increasing application in archaeology as a useful tool to explore movement patterns, exploitation ranges and dispersal (e.g. Herzog 2014), among other human behavioural processes, relevant examples for the Lower Palaeolithic deal mostly with the Later Pleistocene (e.g. Anderson and Gillam 2000; Field, Petraglia and Lahr 2007). This lack of earlier cases is not irrelevant with the limited available evidence (and usually poor in accuracy and resolution) on the Early and Middle Pleistocene palaeogeography and palaeoenvironments, which is crucial for such modelling.

Topographic parameters based on current bathymetric and elevation data (slope, landscape roughness) and elements of the palaeogeography that could have acted as barriers to movement (location of waterbodies over the exposed Aegean landscapes and the location of the palaeocoastline) have been considered for the creation of the cost surface. It is assumed, for modelling purposes, that hominin groups would have taken easier routes, requiring the least effort (cost) to cross the landscape – at least the easiest routes within challenging complex landscapes, such as the Aegean. Effort here is relevant to, and determined by, the topographic configuration. The cost surface in this example represents time of travel, i.e. the time it takes to cross each grid cell to walk from point A to point B, using Tobler's hiking function (Tobler 1993). The speed is affected by topography; smoother terrain permits fastest walking, while complex terrain reduces walking speed.

Archaeological sites from mainland Greece and Western Anatolia have been used as origins and destinations. The selection of the sites is based on general chronological (isochronous sites supported by secure dates) and cultural associations. Due to the fragmented nature of available records and the extensive spatio-temporal discontinuities, it has not been always easy (or even possible) to draw strict and detailed cultural links. For example, for the MIS 10-12, a least-cost route has been calculated between Rodafnidia (origin) and Marathousa 1 (destination) (see Figure 5). Both sites have been dated to the Middle Pleistocene (400-500 Kya) using absolute methods (Galanidou et al. 2016; Panagopoulou et al. 2018) however, the Marathousa 1 industry is attributed to the Mode 1 tradition, while in the assemblage from Rodafnidia an Acheulean technocomplex has been identified with possible African affinities. Nevertheless, hominin groups, even with different traditions, were present at roughly the same time in different areas of the Aegean.

The produced least-cost routes (ArcGIS (ESRI)> spatial analyst extension > distance toolset> cost distance>cost route), travel across the central and northern Aegean, offering a general idea of cost-effective possibilities to cross this area, based on the modern landscape structure and assuming a continuous exposed terrain during the Early and Middle Pleistocene. This is not a straight-forward answer to the question about the traversability potential of the Aegean palaeolandscape and should be treated with caution; firstly because slope is only one factor, out of many, that affect biogeographical processes such as movement, and dispersal, and secondly because modern topography is used in this example as a proxy to provide rough approximations on the natural configuration of the landscape in the past – a palaeo-DEM for the spatial extent of the Aegean case study is not yet available. This modelling is used here merely as a heuristic device, bearing in mind the above-noted limitations and what we have already elaborated earlier about assumed connectivity and contemporaneity in Palaeolithic least-cost routes between sites. It provides a model of what travel on a traversable Aegean terrain during the Lower Palaeolithic between these locations could look like, but should not be taken as suggestive of specific pathways or specific movement patterns during this time. The least-cost route analysis is only a first step towards developing arguments supporting this hypothesis. More parameters could be implemented in this modelling to further investigate hominin mobility and movement patterns, such as energetic costs and palaeoclimate evidence (from the last interglacial).

If we accept the hypothesis that the central and northern Aegean was a traversable terrain during the Lower Palaeolithic, could it also provide viable – in terms of resources – terrestrial pathways for movement and further enable hominin occupation? One of the current authors (P. Tsakanikou) has attempted to assess this possibility, using the concept of suitability, derived from land-use analysis (for an overview see Malczewski 2004), through the development of predictive models for identifying the most appropriate spatial pattern of suitability according to specific parameters.

In the model developed here, suitability refers to conditions that would have favoured hominin presence, survival, and activity, based on the distribution of landscape features corresponding to water resources and volcanic material, natural elements that encompass affordances (sensu Chemero 2003) The selection of the affordance variables is not random but founded upon; (a) observations on topographic complexity, where landscape features related to affordances are located in areas with high topographic complexity and (b) a preferential association with hominins reflecting exploitation and survival opportunities as documented in the existing literature (e.g. Bailey, Reynolds and King 2011; Barboni et al. 2019; Chauhan et al. 2017).

Three zones (0-10km, 10-30km and >30km) were created around specific landscape features such as volcanic centres, palaeolakes, palaeorivers, springs etc., corresponding to the affordance variables. These features are perceived as ‘anchors’ (sensu Golledge 2003) over the landscape and are used as reference points in the spatial analysis. Last Glacial Maximum evidence has been used as a proxy for the earlier parts of the Pleistocene.

The 10km radius, the first zone around the reference points, has been selected as indicative of an exploitation territory during the Lower Palaeolithic, following the ‘site region’ definition given by Bailey & King (2011: 1533). Within the suitability model, a classification system has been developed, ranging from 0 to 3, with 0 indicating the least suitable areas and 3 the most suitable areas. The cells included in the first zone are attributed the value 3 corresponding to areas expected to be the most favourable. As the distance from the reference point increases, the

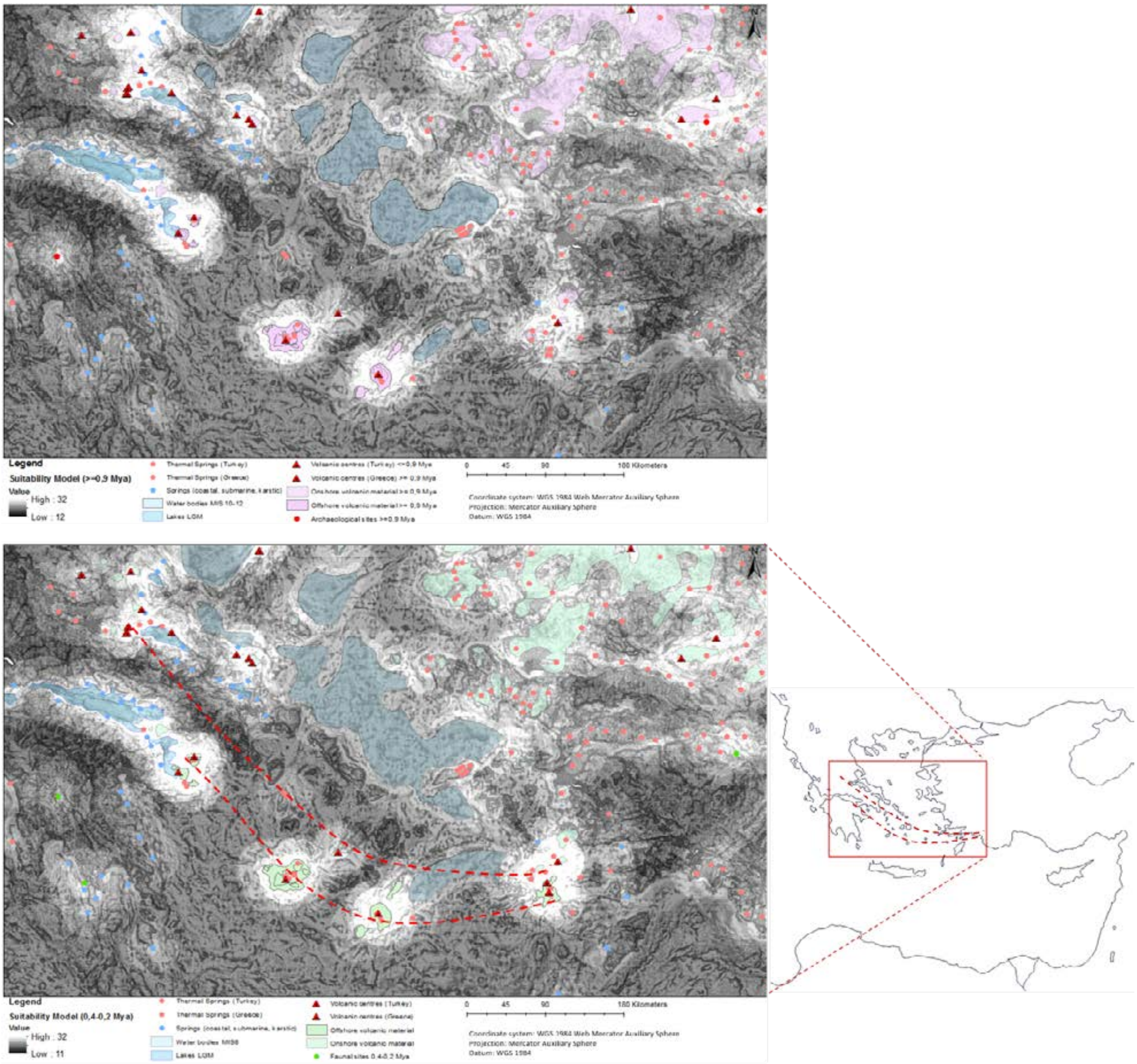

Figure 6. Suitability of the south-central Aegean for the intervals ≥0.9 Mya (top) and 0.4-0.2 Mya (bottom). The colour range from white to black indicates the suitability range from more to less suitable areas. The landscape features corresponding to water resources and volcanic material are visible on the maps, as well as the archaeological, palaeoanthropological and palaeontological sites dated to the specific time intervals. The red dotted line on the main map indicates a corridor with high research potential, at the southern part of the Cycladic Plateau and along the Aegean Volcanic Arc, connecting SW Anatolia and mainland Greece (the 'Volcanic Route Hypothesis'). The maps are produced using ArcMap 10.6.

suitability decreases. Consequently, the second zone is attributed the value 2, and the third zone the value 1. The actual reference points have been attributed the value 0 (representing in the case of the palaeolakes for example the area covered by water).

Each of the reclassified variables are represented by a raster surface, building up the suitability model. In the final raster suitability is indicated through a range of values from the most suitable (white) to the least suitable (black) (see Figure 6). Therefore, it defines possibilities rather than probabilities, which as a concept is more consistent with the fragmented nature of available data from the Aegean region and the use of proxy data. The aim here is to define particular areas, where favourable conditions are indicated by the presence or absence of the selected variables. In that sense, increasing the weight of one variable over the others cannot increase nor decrease the suitability value for a given area. This is why the weighted overlay or the weighted sum have not been selected for the suitability model.

The incorporation of archaeological, palaeoanthropological and palaeontological sites from the study area, securely dated to the Lower Palaeolithic, added a temporal element to the model, with the division into three time intervals ≥0.9 Mya, 0.9-0.4 Mya and 0.4-0.2 Mya, enabling for the first time observations in the changes of suitability over time and space (see Figure 6). Using the complex topography concept, suitability via an affordance approach, and least-cost pathways, the current project aimed to develop and execute new methodological approaches towards a better understanding of the nature of the palaeolandscape as a whole (including geographic sections that now may lie underwater but used to be part of the extended terrestrial Aegean during the Lower Palaeolithic) in order to place hominins within their affording environment. This in turn will allow the development of new models and hypotheses on behavioural aspects such as movement and settlement. This work, albeit preliminary, demonstrates that despite serious methodological challenges and limitations in the Lower Palaeolithic record of the dynamic Aegean, interdisciplinary approaches (archaeology and earth sciences) within a GIS framework offer new valuable insights into the deep past.

The Temptations of Palaeolithic GIS

Palaeolithic archaeology represents a unique research context, based in a unique history for the development of the discipline, but also shaped by the limitations and methodological challenges presented by the available evidence. Its research questions refer to wider processes, such as hominin mobility, landscape use, and exploitation of resources, emerging as patterns over larger spatio-temporal scales. At its most innovative, the use of GIS within the Palaeolithic goes beyond simple use as a tool for prospection or visualisation of data collected through other means. Palaeolithic applications actually have the potential to produce novel datasets, and enable novel arguments, discussions, and interpretations about the hominin record and hominin behaviour that are perhaps not possible without spatial analysis. But the complexities inherent in working with these data are compounded by the fact that the difficulties themselves can push researchers away from studying the more challenging questions or archaeological periods.

Emerging from this tension of complexities is a potential spectrum of effects, which we define here as the three 'temptations' of Palaeolithic GIS;

1. The temptation to follow the data coverage. For instance, if no climate data exist for an earlier period, the temptation is to study a later period with better data coverage.

2. The temptation of allowing the structure of datasets to condition the research questions. For instance, whether the environment is considered as a series of discrete patches of individual biomes, or a continuous landscape of resources is fundamentally a data issue, but it feeds directly into how we imagine hominins to move around a landscape.

3. The temptation to do spatial analyses that are easy to do or are a standard part of the GIS toolkit, although the logic of the record may not support their use. For instance, the use of hydrological analyses because they are commonly applied in later periods, without a specific understanding of what they would relate to in the period and study region in question.

All of these 'temptations' are relevant in later periods as well, but are arguably especially pronounced for Palaeolithic applications. These difficulties all potentially draw research away from research questions that are interesting and valuable from a Palaeolithic perspective, towards questions that perhaps seem easier to answer. Our inquiries, therefore, would be bent to the logic of the analysis, and not to the logic of the record. The net effect has to be a dampening effect on new discoveries as researchers focus on the known archaeological material, and a dampening effect on the development of new methodologies as researchers focus on what is already known to be possible. Ultimately, these effects would represent a move away from more exploratory or innovative methods of analysis in Palaeolithic research.

In both of our case study projects, the present authors have focused on addressing questions about the large scale landscapes and time periods of the Palaeolithic. We aimed to understand and conceptualise wider processes such as hominin mobility and landscape use, and also to develop methodological tools to actualise that understanding in our analyses. In our approaches, and those of others, a variety of different concepts and methodological approaches have been applied to tackle some of these issues; such as affordances (e.g. Webster 1999), accessibility (e.g. Llobera, Fábrega-Álvarez and Parcero-Oubiña 2011), topographic complexity (e.g. Bailey, Reynolds and King 2011; King and Bailey 2006), subsistence-based cost analyses (Whitley et al. 2010), and the averaging and resampling of data. These methodological tools have to make the most of a record with substantial challenges in terms of variable data coverage and variable spatio-temporal scales.

Conclusion

The use of GIS applications in Palaeolithic research is relatively new as a research field, and as such, it necessitates innovation and experimentation as a part of the process of full integration and realisation. To encourage that process, Palaeolithic GIS needs an explicitly theoretical discussion to complement its existing practical focus, and to support the growth of junior researchers and innovative methodologies. We have endeavoured to make these arguments concrete with reference to examples from our own doctoral projects in Central Asia and the Aegean. In the process, we have defined three challenges and three temptations of Palaeolithic applications of GIS, which are meant as theoretical discussion points;

Three challenges of Palaeolithic applications of GIS;

1. poor data coverage

2. vast spatio-temporal scale

3. the difficulty of inferring behavioural patterns under the conditions of problems 1. and 2.

Three temptations of Palaeolithic applications of GIS;

1. to follow the data coverage, rather than to try to generate data for difficult places and periods

2. to adapt questions to the logic of data structure, rather than rework data to suit questions

3. to do analyses that are familiar but irrelevant, rather than pioneer new methodological solutions

These points are meant to underline the necessity of an explicitly theoretical discussion for the development of Palaeolithic GIS. In the absence of guidelines representing acceptable approaches or best practice, the current best practice must be considered to be 'tailor-made', as researchers struggle with their unique research questions, issues of data availability, and the limitations of the standard GIS toolkit. Only by beginning to define these terms in discussion can we begin to develop our sub-discipline as a self-reflective and theoretically explicit field. The result of this process must be to better understand our goals and directions for development of the field, which will be crucial in developing and properly realising its interactions and borrowings from allied fields such as geology and geomorphology.

The CAA2018 Palaeo-GIS session was a good forum to start discussing these issues, and it became clear that many researchers shared our concerns in these areas. We should not expect definitive answers, but rather an opening of dialogue that permits us to make suggestions, discuss possibilities, and develop scenarios that can offer some new insights in the ways we record, study, and interpret early human behaviour over larger spatio-temporal scales.

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References

Anderson, D G and Gillam, J C 2000 Paleoindian Colonization of the Americas: Implications from an Examination of Physiography, Demography, and Artifact Distribution, *American Antiquity*, 65(1): 43–66. DOI: https://doi.org/10.2307/2694807

Anemone, R L, Conroy, G C and Emerson, C W 2011 GIS and paleoanthropology: Incorporating new approaches from the geospatial sciences in the analysis of primate and human evolution, *American Journal of Physical Anthropology*, 146(S53): 19–46. DOI: https://doi.org/10.1002/ajpa.21609

Bailey, G N and King, G C P 2011 Dynamic landscapes and human dispersal patterns: tectonics, coastlines, and the reconstruction of human habitats, *Quaternary Science Reviews*, 30(11): 1533–1553. DOI: https://doi.org/10.1016/j.quascirev.2010.06.019

Bailey, G N, Reynolds, S C and King, G C P 2011 Landscapes of human evolution: models and methods of tectonic geomorphology and the reconstruction of hominin landscapes, *Journal of Human Evolution*, 60(3): 257–280. DOI: https://doi.org/10.1016/j.jhevol.2010.01.004.

Barboni, D, Ashley, G, Bourel, B, Arráiz, H and Mazur, J-C 2019 Springs, palm groves, and the record of early hominins in Africa, *Review of Palaeobotany and Palynology*, 266: 23–41. DOI: https://doi.org/10.1016/j.revpalbo.2019.03.004.

Breeze, P S, Drake, N A, Groucutt, H S, Parton, A, Jennings, R P, White, T S, Clark-Balzan, L, Shipton, C, Scerri, E M L, Stimpson, C M, Crassard, R, Hilbert, Y, Alsharekh, A, Al-Omari, A and Petraglia, M D 2015 Remote sensing and GIS techniques for reconstructing Arabian palaeohydrology and identifying archaeological sites, *Quaternary International*, 382: 98–119. DOI: https://doi.org/10.1016/j.quaint.2015.01.022

Breeze, P S, Groucutt, H S, Drake, N A, Louys, J, Scerri, E M L, Armitage, S J, Zalmout, I S A, Memesh, A M, Haptari, M A, Soubhi, S A, Matari, A H, Zahir, M, Al-Omari, A, Alsharekh, A M and Petraglia, M D 2017 Prehistory and palaeoenvironments of the western Nefud Desert, Saudi Arabia, *Archaeological Research in Asia*, 10: 1–16. DOI: https://doi.org/10.1016/j.ara.2017.02.002

Breeze, P S, Groucutt, H S, Drake, N A, White, T S, Jennings, R P and Petraglia, M D 2016 Palaeohydrological corridors for hominin dispersals in the Middle East ~250–70,000 years ago, *Quaternary Science Reviews*, 144: 155–185. DOI: https://doi.org/10.1016/j.quascirev.2016.05.012

Brouwer Burg, M 2013 Reconstructing "total" paleo-landscapes for archaeological investigation: an example from the central Netherlands, *Journal of Archaeological Science*, 40(5): 2308–2320. DOI: https://doi.org/10.1016/j.jas.2013.01.008

Chauhan, P R, Bridgland, D R, Moncel, M-H, Antoine, P, Bahain, J-J, Briant, R, Cunha, P P, Despriée, J, Limondin-Lozouet, N, Locht, J-L, Martins, A A, Schreve, D C, Shaw, A D, Voinchet, P, Westaway, R, White, M J and White, T S 2017 Fluvial deposits as an archive of early human activity: Progress during the 20 years of the Fluvial Archives Group, *Quater-*

nary Science Reviews, 166: 114–149. DOI: https://doi.org/10.1016/j.quascirev.2017.03.016

Chemero, A 2003 An Outline of a Theory of Affordances, *Ecological Psychology*, 15(2): 181–195. DOI: https://doi.org/10.1207/S15326969ECO1502_5

Coil, R, Tappen, M, Ferring, R, Bukhsianidze, M, Nioradze, M and Lordkipanidze, D 2020 Spatial patterning of the archaeological and paleontological assemblage at Dmanisi, Georgia: An analysis of site formation and carnivore-hominin interaction in Block 2, *Journal of Human Evolution*, 143: 102773. DOI: https://doi.org/10.1016/j.jhevol.2020.102773

Conolly, J and Lake, M 2006 *Geographical Information Systems in Archaeology*. Cambridge University Press.

Cuthbertson, P, Ullmann, T, Büdel, C, Varis, A, Namen, A, Seltmann, R, Reed, D, Taimagambetov, Z and Iovita, R 2021 Finding karstic caves and rockshelters in the Inner Asian mountain corridor using predictive modelling and field survey, *PLOS ONE*, 16(1): e0245170. DOI: https://doi.org/10.1371/journal.pone.0245170

Dennell, R W, Martinón-Torres, M and Bermúdez de Castro, J M 2011 Hominin variability, climatic instability and population demography in Middle Pleistocene Europe, *Quaternary Science Reviews*, 30(11): 1511–1524. DOI: https://doi.org/10.1016/j.quascirev.2009.11.027

Ferring, R, Oms, O, Agustí, J, Berna, F, Nioradze, M, Shelia, T, Tappen, M, Vekua, A, Zhvania, D and Lordkipanidze, D 2011 Earliest human occupations at Dmanisi (Georgian Caucasus) dated to 1.85–1.78 Ma, *Proceedings of the National Academy of Sciences*, 108(26): 10432–10436. DOI: https://doi.org/10.1073/pnas.1106638108

Field, J S and Lahr, M M 2005 Assessment of the Southern Dispersal: GIS-Based Analyses of Potential Routes at Oxygen Isotopic Stage 4, *Journal of World Prehistory*, 19(1): 1–45.

Field, J S, Petraglia, M D and Lahr, M M 2007 The southern dispersal hypothesis and the South Asian archaeological record: Examination of dispersal routes through GIS analysis, *Journal of Anthropological Archaeology*, 26(1): 88–108. DOI: https://doi.org/10.1016/j.jaa.2006.06.001

Foley, R 1981 Off-site archaeology: an alternative approach for the short-sighted. In: Clarke, D L and Glynn, I (eds.) *Pattern of the Past: Studies in the Honour of David Clarke.* Cambridge: Cambridge University Press. pp. 157–183.

Gaffney, V and van Leusen, M 1995 Postscript - GIS, environmental determinism and archaeology: a parallel text. In: Lock, G R and Stančič, Z (eds.) *Archaeology and geographic information systems: A European perspective.* Boca Raton: CRC Press. pp. 367–382.

Galanidou, N, Athanassas, C, Cole, J, Iliopoulos, G, Katerinopoulos, A, Magganas, A and McNabb, J 2016 The Acheulian Site at Rodafnidia, Lisvori, on Lesbos, Greece: 2010–2012. In: Harvati, K and Roksandic, M (eds) *Paleoanthropology of the Balkans and Anatolia: Human Evolution and its Context. Vertebrate Paleobiology and Paleoanthropology*. Dordrecht: Springer Netherlands. pp. 119–138. DOI: https://doi.org/10.1007/978-94-024-0874-4_8

Galanidou, N, Cole, J, Iliopoulos, G and McNabb, J 2013 East meets West: The Middle Pleistocene site of Rodafnidia on Lesvos, Greece, *Antiquity* Project Gallery, 87(336): http://antiquity.ac.uk/projgall/galanidou336/

García-Moreno, A, Hutson, J M, Villaluenga, A, Turner, E and Gaudzinski-Windheuser, S 2021 A detailed analysis of the spatial distribution of Schöningen 13II-4 'Spear Horizon' faunal remains, *Journal of Human Evolution*, 152: 102947. DOI: https://doi.org/10.1016/j.jhevol.2020.102947

Gibson, J J 1986 *The Ecological Approach to Visual Perception*. Psychology Press.

Golledge, R G 2003 Human wayfinding and cognitive maps. In: Rockman, M. and Steele, J. (eds.) *Colonizing unfamiliar landscapes: the archaeology of adaptation.* Abingdon, UK: Taylor & Francis, Routledge. pp. 25–43.

Harvati, K 2016 Paleoanthropology in Greece: Recent Findings and Interpretations. In: Harvati, K and Roksandic, M (eds.) *Paleoanthropology of the Balkans and Anatolia: Human Evolution and its Context. Vertebrate Paleobiology and Paleoanthropology*. Dordrecht: Springer Netherlands. pp. 3–14. DOI: https://doi.org/10.1007/978-94-024-0874-4_1

Herzog, I 2014 A review of case studies in archaeological least-cost analysis, *Archeologia e Calcolatori*, 25: 223–239.

Herzog, I 2020 Spatial Analysis Based on Cost Functions. In: Gillings, M., Hacıgüzeller, P., and Lock, G. (eds.) *Archaeological Spatial Analysis: A Methodological Guide*. Routledge, pp. 333–358.

Holmes, K M 2007 Using Pliocene palaeoclimatic data to postulate dispersal pathways of early hominins, *Palaeogeography, Palaeoclimatology, Palaeoecolo-*

gy, 248(1): 96–108. DOI: https://doi.org/10.1016/j.palaeo.2006.11.012

Hopkirk, K 1993 *Central Asia through writer's eyes*. London: Eland.

Jennings, R P, Shipton, C, Breeze, P, Cuthbertson, P, Bernal, M A, Wedage, W M C O, Drake, N A, White, T S, Groucutt, H S, Parton, A, Clark-Balzan, L, Stimpson, C, al Omari, A-A, Alsharekh, A and Petraglia, M D 2015 Multi-scale Acheulean landscape survey in the Arabian Desert, *Quaternary International*, 382: 58–81. DOI: https://doi.org/10.1016/j.quaint.2015.01.028

Kahlke, R-D, García, N, Kostopoulos, D S, Lacombat, F, Lister, A M, Mazza, P P A, Spassov, N and Titov, V V 2011 Western Palaearctic palaeoenvironmental conditions during the Early and early Middle Pleistocene inferred from large mammal communities, and implications for hominin dispersal in Europe, *Quaternary Science Reviews*, 30(11): 1368–1395. DOI: https://doi.org/10.1016/j.quascirev.2010.07.020

Kamermans, H and Rensink, E 1999 GIS in Palaeolithic Archaeology. A Case Study from the Southern Netherlands. In: Dingwall, L., Exon, S., Gaffney, V., Laflin, S., and van Leusen, M. (eds.) *Archaeology in the Age of the Internet. CAA97. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 25th Anniversary Conference, University of Birmingham, April 1997. BAR international series*. Oxford: Archaeopress. pp. 20–33.

King, G and Bailey, G 2006 Tectonics and human evolution, *Antiquity*, 80(308): 265–286. DOI: https://doi.org/10.1017/S0003598X00093613

Li, F, Vanwezer, N, Boivin, N, Gao, X, Ott, F, Petraglia, M and Roberts, P 2019 Heading north: Late Pleistocene environments and human dispersals in central and eastern Asia, *PLOS ONE*, 14(5): e0216433. DOI: https://doi.org/10.1371/journal.pone.0216433

Llobera, M, Fábrega-Álvarez, P and Parcero-Oubiña, C 2011 Order in movement: a GIS approach to accessibility, *Journal of Archaeological Science*, 38(4): 843–851. DOI: https://doi.org/10.1016/j.jas.2010.11.006

Lock, G R 2000 *Beyond the Map: Archaeology and Spatial Technologies*. IOS Press.

Lock, G and Stančič, Z 1995 *Archaeology and Geographic Information Systems: A European Perspective.*

Lykousis, V 2009 Sea-level changes and shelf break prograding sequences during the last 400ka in the Aegean margins: Subsidence rates and palaeogeographic implications, *Continental Shelf Research*, 29(16): 2037–2044. DOI: https://doi.org/10.1016/j.csr.2008.11.005

Malczewski, J 2004 GIS-based land-use suitability analysis: a critical overview, *Progress in Planning*, 62(1): 3–65. DOI: https://doi.org/10.1016/j.progress.2003.09.002

Neruda, P 2017 GIS analysis of the spatial distribution of Middle Palaeolithic artefacts in Kůlna Cave (Czech Republic), *Quaternary International*, 435: 58–76. DOI: https://doi.org/10.1016/j.quaint.2015.10.028

Otto-Bliesner, B L, Marshall, S J, Overpeck, J T, Miller, G H, Hu, A and Members, C L I P 2006 Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation, *Science*, 311(5768): 1751–1753. DOI: https://doi.org/10.1126/science.1120808

Panagopoulou, E, Tourloukis, V, Thompson, N, Athanassiou, A, Tsartsidou, G, Konidaris, G, Giusti, D, Karkanas, P and Harvati, K 2015 Marathousa 1: a new Middle Pleistocene archaeological site from Greece, *Antiquity* Project Gallery, 89(343): http://antiquity.ac.uk/projgall/panagopoulou343.

Panagopoulou, E, Tourloukis, V, Thompson, N, Konidaris, G, Athanassiou, A, Giusti, D, Tsartsidou, G, Karkanas, P and Harvati, K 2018 The Lower Palaeolithic site of Marathousa 1, Megalopolis, Greece: Overview of the evidence, *Quaternary International*, 497: 33–46. DOI: https://doi.org/10.1016/j.quaint.2018.06.031

Ranov, V A and Dodonov, A E 2003 Small instruments of the Lower Palaeolithic site Kuldara and their geoarchaeological meaning. In: Burdukiewicz, J M and Ronen, A (eds) Lower Palaeolithic Small Tools in Europe and the Levant. Banbury: *British Archaeological Reports*. pp. 133–147.

Sakellariou, D and Galanidou, N 2016 Pleistocene submerged landscapes and Palaeolithic archaeology in the tectonically active Aegean region, *Geological Society, London, Special Publications*, 411(1): 145–178. DOI: https://doi.org/10.1144/SP411.9

Sakellariou, D and Galanidou, N 2017 Aegean Pleistocene Landscapes Above and Below Sea-Level: Palaeogeographic Reconstruction and Hominin Dispersals. In: Bailey, G N, Harff, J, and Sakellariou, D (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf. Coastal Research Library. Cham: Springer International Publishing*. pp. 335–359. DOI: https://doi.org/10.1007/978-3-319-53160-1_22

Sauer, F, Stott, D and Riede, F 2018 Search for new final Palaeolithic rock shelter sites in the Federal State of Hesse, *Journal of Archaeological Science: Reports*, 22: 168–178. DOI: https://doi.org/10.1016/j.jasrep.2018.09.021

Spassov, N 2016 Southeastern Europe as a Route for the Earliest Dispersal of Homo Toward Europe: Ecological Conditions and the Timing of the First Human Occupation of Europe. In: Harvati, K and Roksandic, M (eds) *Paleoanthropology of the Balkans and Anatolia: Human Evolution and its Context. Vertebrate Paleobiology and Paleoanthropology*. Dordrecht: Springer Netherlands. pp. 281–290. DOI: https://doi.org/10.1007/978-94-024-0874-4_16

Spikins, P and Engen, M 2010 Putting Predictive Models Underwater, Challenges New Perspectives and Potential of GIS Based Predictive Models in Submerged Areas. In: Nicolucci, F and Hermon, S (eds) *Beyond the Artifact. Digital Interpretation of the Past. Proceedings of CAA2004*, Prato 13–17 April 2004. Budapest: Archaeolingua. pp. 266–270.

Tobler, W 1993 *Three Presentations on Geographical Analysis and Modeling: Non-Isotropic Geographic Modeling; Speculations on the Geometry of Geography; and Global Spatial Analysis*. National Center For Geographic Information And Analysis, Technical Report, 93 -1.

Tourloukis, V 2010 *The Early and Middle Pleistocene Archaeological Record of Greece: Current Status and Future Prospects*. Amsterdam University Press.

Tsakanikou, P, Galanidou, N and Sakellariou, D 2020 *Lower Palaeolithic archaeology and submerged landscapes in Greece: The current state of the art, Quaternary International*, DOI: https://doi.org/10.1016/j.quaint.2020.05.025

Tsakanikou, P and McNabb, J 2020 Exploring hominin movement patterns in the Lower Palaeolithic Aegean dry land: methodological challenges. In: Raad, N and Carbera-Tejedor, C (eds) *Ships, Boats, Ports, Trade, and War in the Mediterranean and Beyond. Proceedings of the Maritime Archaeology Graduate Symposium* 2018. p. 149.

Webster, D S 1999 The concept of affordance and GIS: a note on Llobera (1996), *Antiquity*, 73(282): 915–917. DOI: https://doi.org/10.1017/S0003598X00065698

Whitley, T, Moore, I, Goel, G and Jackson, D 2010 Beyond the Marsh: Settlement Choice, Perception, and Spatial Decision-making on the Georgia Coastal Plain. In: Frischer, B, Webb Crawford, J, and Koller, D (eds.) *Making History Interactive. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, March 22-26 (BAR International Series S2079)*. Oxford: Archaeopress. pp. 380–390.

Zhu, Z, Dennell, R, Huang, W, Wu, Y, Qiu, S, Yang, S, Rao, Z, Hou, Y, Xie, J, Han, J and Ouyang, T 2018 Hominin occupation of the Chinese Loess Plateau since about 2.1 million years ago, *Nature*, 559(7715): 608–612. DOI: https://doi.org/10.1038/s41586-018-0299-4

3-Dimensional Analysis

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2018

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A Browser-Based 3D Scientific Visualisation of the Keros Excavations

Dante Abate
STARC, The Cyprus Institute
d.abate@cyi.ac.cy

Marina Faka
STARC, The Cyprus Institute
m.faka@cyi.ac.cy

Sorin Hermon
STARC, The Cyprus Institute,
s.hermon@cyi.ac.cy

James Herbst
American School of Classical Studies at Athens, james@jamesherbst.net

Evi Margaritis
STARC, The Cyprus Institute
e.margaritis@cyi.ac.cy

Michael J. Boyd
STARC, The Cyprus Institute & McDonald Institute for Archaeological Research, University of Cambridge,
mjb235@cam.ac.uk

Colin Renfrew
McDonald Inst. for Archaeological Research, Univ. of Cambridge
acr10@cam.ac.uk

Abstract

During 2007-2008 and again in 2016-2018 the McDonald Institute of the University of Cambridge, and in collaboration with The Cyprus Institute during the later campaign, has been conducting excavation on the small islet of Dhaskalio, just off the west coast of the Cycladic island of Keros in Greece. Today inhabited, the island was the site of the world's earliest maritime sanctuary (ca. 2750-2300 BC). Recent excavations are highlighting the remarkable monumentality of the proto-urban settlement adjacent to the sanctuary, which shows precocious evidence for metalworking and agricultural intensification. The comprehensive paper-free digital recording strategy (to be described in full elsewhere) includes an iPad-based recording system (iDig) used in the field and in the laboratory, producing a single excavation database. Spatially, individual contexts are recorded using photogrammetry. Additionally, each excavation trench is 3D documented by means of a terrestrial laser – scanner. The latter aspect of the work is reported in detail here.

Keywords: Web visualization, digital archaeology, Laser Scanning, Photogrammetry, Early Bronze Age, Cyclades

Introduction

Aims of the 3D Documentation Project

The archaeological site under investigation (Renfrew et al. 2007; Renfrew et al. 2009, Renfrew et al. 2012; Renfrew 2013) many various parts of the islet and presents challenges in its excavation, due to the

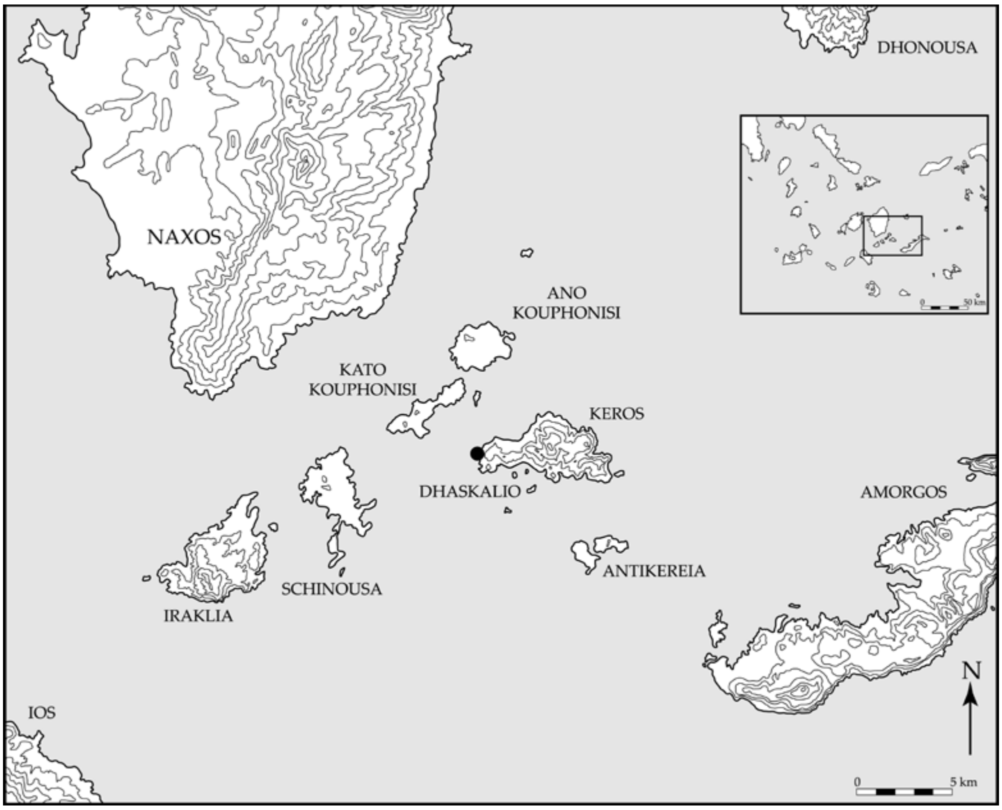

Figure 1. Location of Keros, south of Naxos, Cycladic Islands, Greece (Image credit: The Cambridge Keros Project, McDonald Institute for Archaeological Research, University of Cambridge, UK)

complexity and uniqueness of its architectural and material culture remains, as well as the challenging topography and accessibility of the islet. Consequently, an aerial photographic survey conducted in 2008 (Patias et al. 2009) by means of a remote-controlled helicopter returned a set of images that were processed in order to obtain a 3D model of the entire islet, as a first and overall platform for identification of main concentrations of archaeological remains and for the later positioning and integration of the 3D models of the various components of the excavation. In 2016 and 2017 eight new excavation trenches were opened. A series of surveyed targets were positioned along the site in order to geo-reference the excavation data: individual contexts, entire trenches or architectural complexes. Products of the photogrammetric workflow, such as orthophoto mosaics and digital elevation models, are integrated within the GIS currently being developed for the entire excavation dataset. Furthermore, these targets were used to geo-reference the two campaigns of laser-scanning documentation, carried out at the end of each of the 2016 and 2017 seasons and aiming to fully 3D document each trench at the end of the excavation seasons.

The paper reports on the integration of the whole-island aerial and terrestrial image-based 3D modelling with the terrestrial laser-scanning data, in order to: (a) create an easily accessible platform for the browser-based visualisation and investigation of 3D data and (b) integrate all 3D data produced at the site within a single system, and thus virtually re-creating the excavation process in an inverse diachronic sequence. Each of the 3D single entities were integrated within the browser-based visualisation system, where users can visualise the entire island, select trenches and perform various measurements, such as distances, depth, area, volume, extraction and comparison of cross-sections. Moreover, they can select single excavation units for further similar investigations. It further envisaged that as the GIS platform develops, 3D models will be integrated within it.

Related Works

The 3D documentation of structures and excavation is today a standard practice in archaeology. A multi-resolution approach and the integration of different modelling technologies and methodologies can provide the best results for integrating landscape, structures, stratigraphic excavation and

Figure 2. Dhaskalio promontory, aerial view

finds (Ramos and Remondino 2015). Indeed, different projects have highlighted the potential of image- and range-based modelling in the heritage sector. In Gruen, Remondino and Zhang, (2005), a multi-resolution approach exploiting passive sensors is presented for the documentation of the valley of Bamiyan where the giant statues of Buddhas existed before they were destroyed by the Taliban in 2001. A GIS database has been realized for the UNESCO area. A 3D multi- resolution approach was applied at the Rucellai's chapel in Florence (Bonora, Tucci, and Vaccaro, 2005). The authors present a new complete survey aimed to support restoration tasks. El-Hakim, Remondino and Voltolini (2008) integrated drawings, images and range data for the modelling of castles and their landscapes. Starting from the extrusion of massive models from 2D plans, the architecture could be studied and areas requiring more accurate modelling could be defined.

A multi-resolution and multi-sensor approach has been developed by Guidi et al. (2008; 2009) for the accurate and detailed 3D modelling of the entire Roman Forum in Pompei in Italy, by 3D scanning of a XIXth century plaster model of Imperial Rome. Active and passive sensors were used for the digital documentation of the archaeological site trying to fulfil all the surveying and archaeological needs and exploit all the intrinsic potentialities of the actual 3D modelling techniques.

Remondino et al. (2009) presented a reality-based project, exploiting multi-resolution and multi-source documentation for the digital reconstruction of part of the Maya archaeological site of Copán, Honduras. The final goals were to provide digital 3D models for research and public education purposes.
In Cantoro (2017), a 3D approach is proposed for the integration of aerial and terrestrial data accessible through a web-based platform. Hermon et al. (2017) discuss the use of 3D documentation in exploring how ancient buildings were constructed and possibly used, based on structural and architectural analyses, while in (Faka et al., 2017) a 3D based functional analysis of how ancient buildings functioned is presented.

Abate and Sturdy-Colls (2018) presented the use of digital 3D technologies and web visualization tools for the analysis of the Treblinka extermination and labour camps in Poland, providing a digital interactive platform, which can be used both by professional users and a public audience. The authors propose a pyramidal multi-level and multi-sensor approach – providing a 3D resolution spanning from a few centimetres in the landscape Digital Terrain Model to few millimetres in the layer-by-layer archaeological test trench;

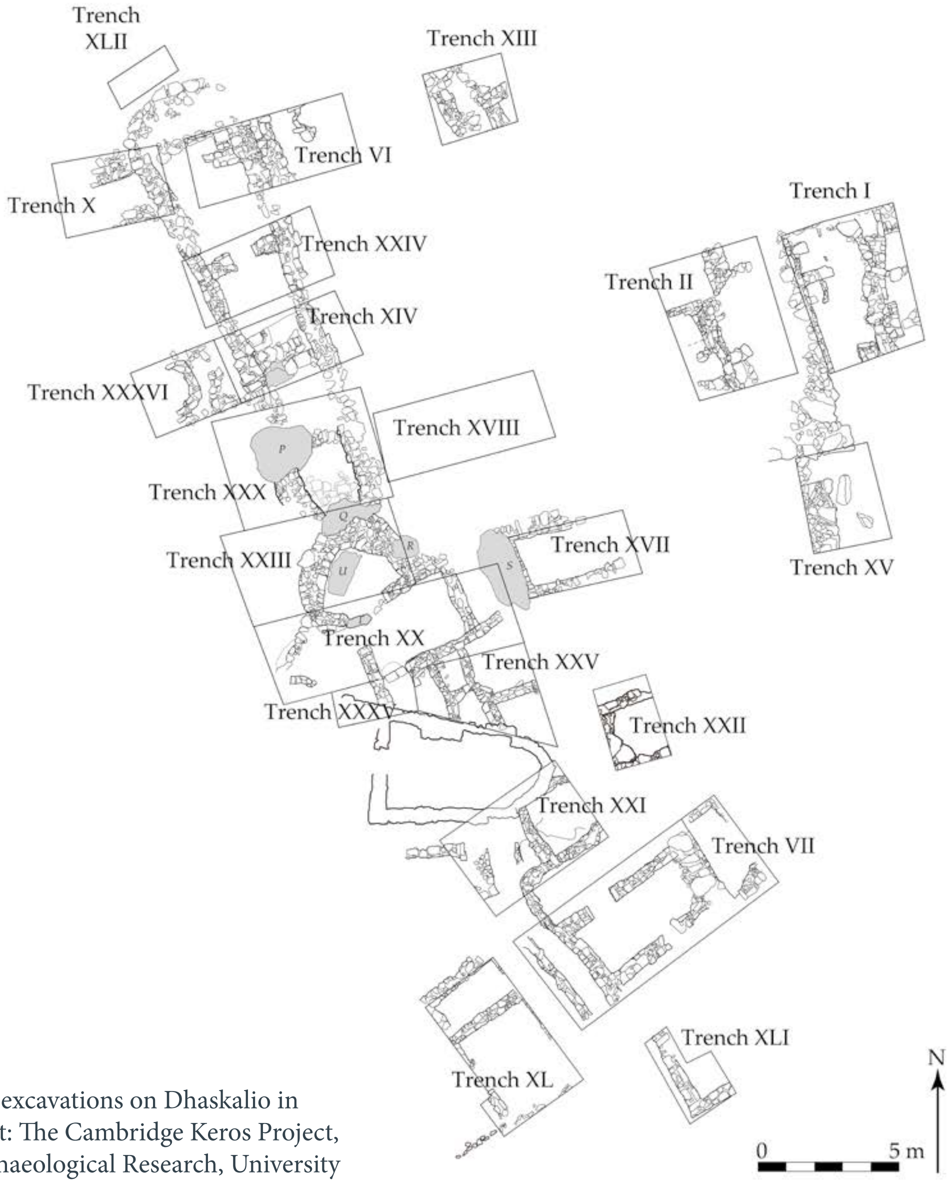

Figure 3. Plan of part of the excavations on Dhaskalio in 2007 and 2008 (Image credit: The Cambridge Keros Project, McDonald Institute for Archaeological Research, University of Cambridge, UK)

Archaeological Description of the Archaeological Site and Recent Excavation Seasons

Excavations at the site unveiled the world's earliest maritime sanctuary (2750-2250 BCE), where during the Early Bronze Age (EBA) travellers came from all over the Cyclades (and beyond) to deposit fragmented choice material (marble figurines and bowls, special ceramic items, and obsidian) in two 'special deposits', while pedestrian surveys conducted between 2012-3 revealed the existence of a dozen or so other small settlements from the same period (Figure 1).

One of them, and once connected to the main island of Keros through an isthmus nowadays underwater, is the pyramid-shaped rocky islet of Dhaskalio, rising at 35m ASL (Figure 2).

The site was excavated in two seasons, during 2007-2008 and 2016-2018 respectively. The first excavation season focused on the remains located on the summit area, where an elongated building was identified. During 2016-2018 campaigns the excavations focused on the lower levels of the islet. These have shown that there were constructions all over the promontory, using a system of massive terraces on which house walls were built. A survey of the rest of Dhaskalio identified remnants of walls located all over the islet. Domestic and non-domestic architec-

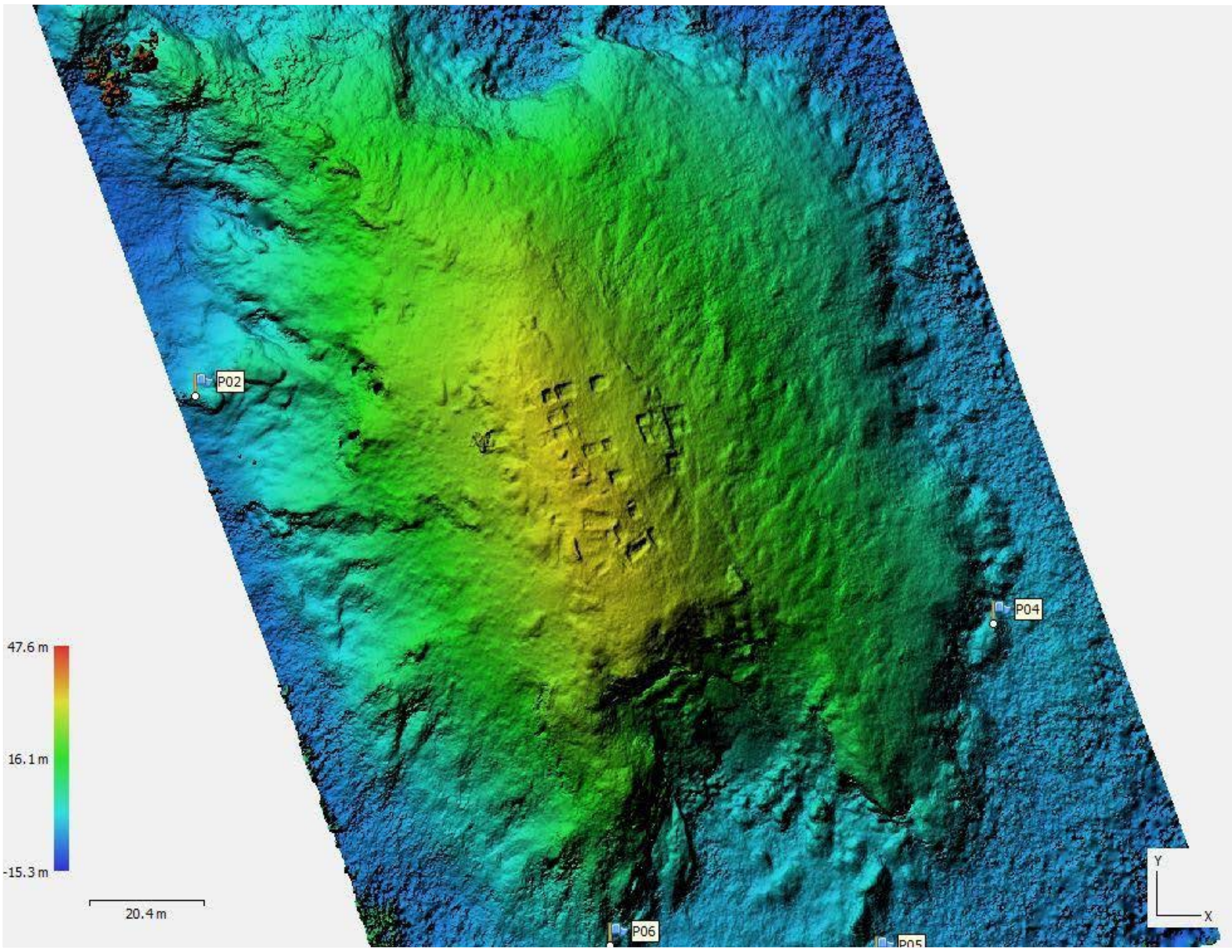

Figure 4. Dhaskalio, Digital Elevation Model

ture, the evidence of metallurgy and the complexity of remains indicate a rich and complex nature of the archaeological site, with possible antecedents to the later urbanism of major centres such as Knossos (Figure 3).

3D Data Capturing Methodology

The study described in this paper focuses on the 3D modelling and visualisation work, consisting of a top-down multi-scale image-and range-based digital documentation method developed to fulfil all the surveying and archaeological needs and exploit all the intrinsic potential of current geomatics techniques.

Image based Techniques

Since the early stages of the excavation in Keros, various kind of sensors and approaches were used for the site accurate documentation (Patias et al., 2009). Due to its portability and reliability, photogrammetry has been extensively used both from aerial and terrestrial platforms.

During 2008 an aerial survey was realised by means of an Unmanned Aerial Vehicle (UAV) with the main aim being to create a Digital Elevation Model (DEM) of the island of Dhaskalio, providing an overview of the site morphology. With the main aim to scale the model to real-world measurements natural features of the archaeological excavation were used as GCPs and CPs, bearing a RMS error of 4 cm (Figure 4).

During the 2016 and 2017 seasons UAV airborne photogrammetry continued to be used to create DEMs, orthophotos and 3D mesh models, and terrestrial photogrammetry was added to the spatial recording methods of the excavations. Terrestrial photogrammetry held the goal to create a 3D model for each excavated context so that a trench could

Figure 5. Trench L deposit, image-based 3D model

be virtually re-excavated at any time in the future. In the field, photographers use handheld 16 MP cameras take between 30 and 300 image captures, according with the trench dimensions (Figure 5). The camera parameters have been set as following: Focal Length 22mm; ISO 100, f/8. A number of coded targets are captured in the scene as well with a twofold final goal: georeference each deposit in the same reference system and apply a metric scale to each three-dimensional reconstruction. The typical photogrammetric workflow has been applied, consisting of three main steps, namely: image correspondences detection, bundle adjustment and dense image matching (Remondino et al., 2014).

At the end of the photogrammetric documentation process, each of the individual excavation units are separately documented as a single 3D model,subsequently to be re-composed and merged within a single diachronic 3D model, while maintaining their geometric shape, which corresponds to the excavation process itself. Thus, the entire excavation volume with its features, material culture remains as they were found, and architectonic remains has been 3D documented and aligned within a single 3D volume.

Trench	2016 Excavation	2017 Excavation
A	√	√
B	X	√
C	√	√
E	X	√
F	X	√
H	√	√
L	√	√
N	X	√
SB	√	X
Wall A	√	X
North Wall	√	X

Table I: Terrestrial Laser Scanning Surveys, documented trenches

Range Based Technique

Two range-based surveys were performed at the end of each archaeological campaign (2016 and 2017) with the main aim being to document the trenches and the whole progress of the excavation during a one-year period (Δt). Moreover, during 2017, new

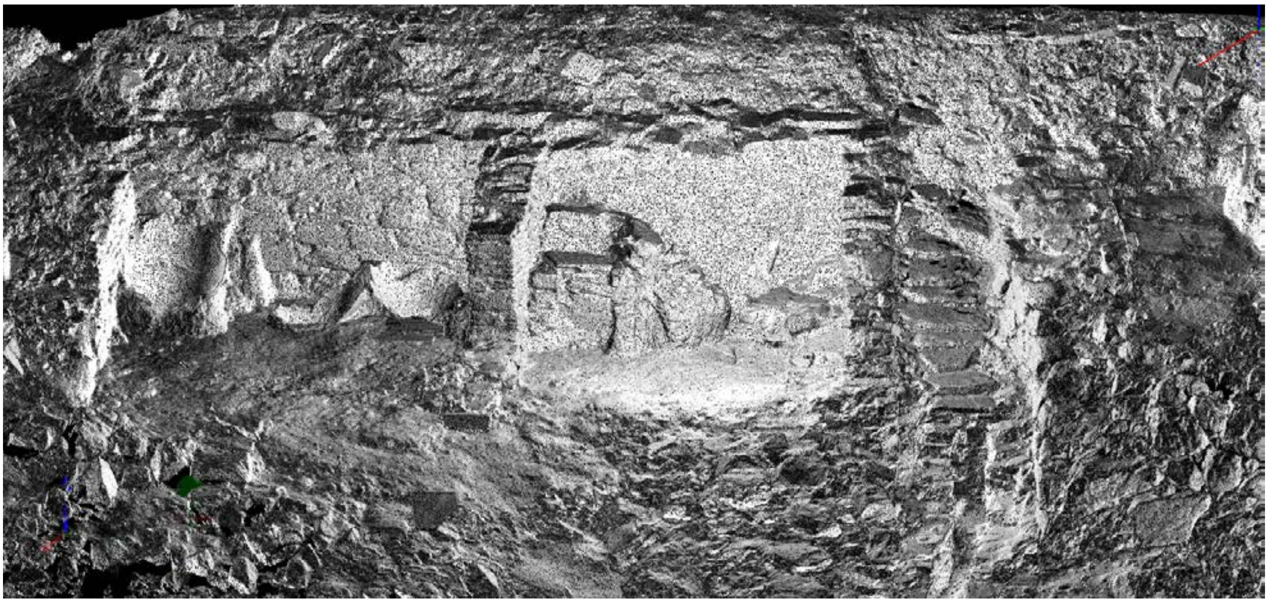

Figure 6. Trench H, Terrestrial Laser Scan 3D model

trenches were opened and documented for the first time (Table I). Thus, trenches that were excavated two years in a row were documented twice, while trenches opened in 2017 were documented once (Further TLS survey also took place in 2018, not further discussed here).

The range-based survey was realized using two Terrestrial Laser Scanners (TLSs) yielding an average distance scanner-object of 5 meters with a mean resolution of 3.5 mm per scan. A standard post processing pipeline, using JRC Reconstructor software, was then applied (Mills and Andrews, 2011). After the range maps registration, which resulted in a mean RMS error of ~5mm, each trench was manually cleaned and filtered in order to remove external noise and unwanted data. A merged model for each single trench was finally created with an average spacing of ~1 cm (Figure 6). The number of scans per trench was a-priori planned to capture all the archaeological attributes visible at the end of each excavation campaign (Table II). Since the extent of each area was slightly expanded between the two seasons, in 2017 the number of scans was increased to capture newly unearthed archaeological features in depth.

Exploiting the photogrammetric GCPs network, collected by means of a DGPS, each point cloud was finally georeferenced in the local reference system, so to meet the requirements for the integration in the web-based visualization system described below.

Trench	Number of Scans 2016	Number of Scans 2017
A	19	58
B	X	25
C	12	36
E	X	19
F	16	32
H	21	37
L	13	30
N	X	19
SB	7	X
Wall A	21	X
North Wall	11	X

Table II: Number of stations per single trench

Digital Preservation - Browser-Based System

With the main aim of creating an easy-to-use interactive platform for the Keros archaeological site, open both for professional and general use, all the models and 3D information have been organised in a single web-based interactive application. In accord with the initial pyramidal approach, the user is able to browse the virtual objects from a landscape to a layer-by-layer scale in the same virtual environment. The web-based system, which can be exploited using

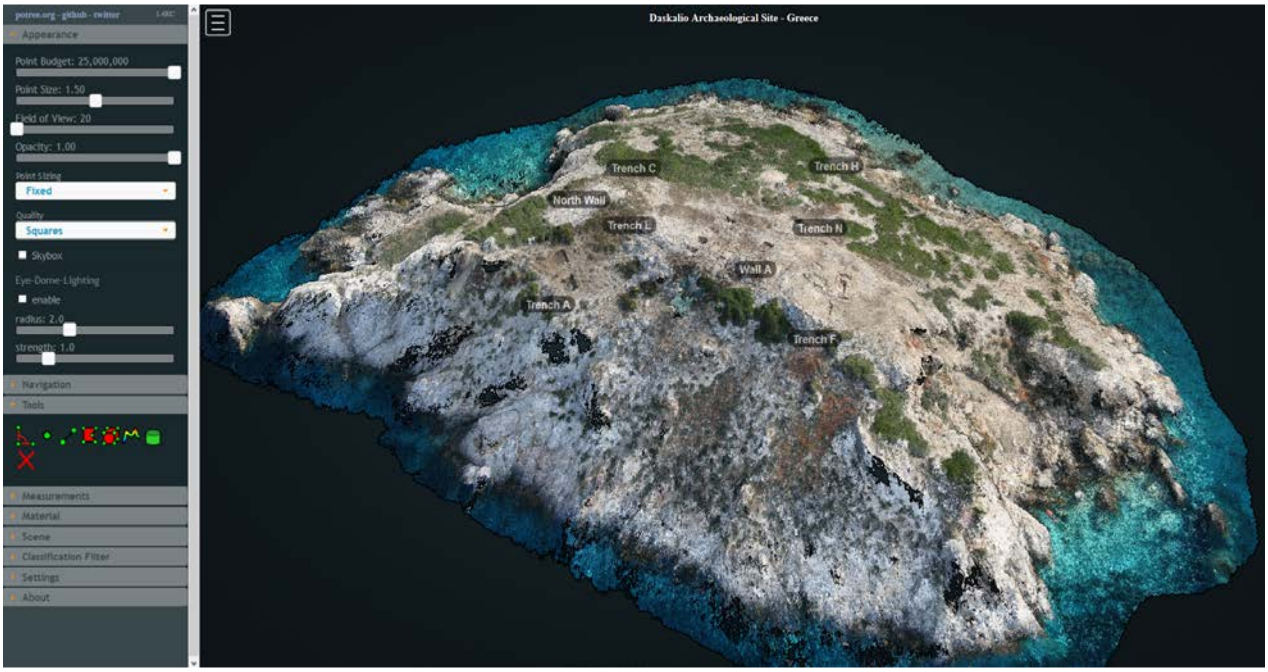

Figure 7. Web visualization system

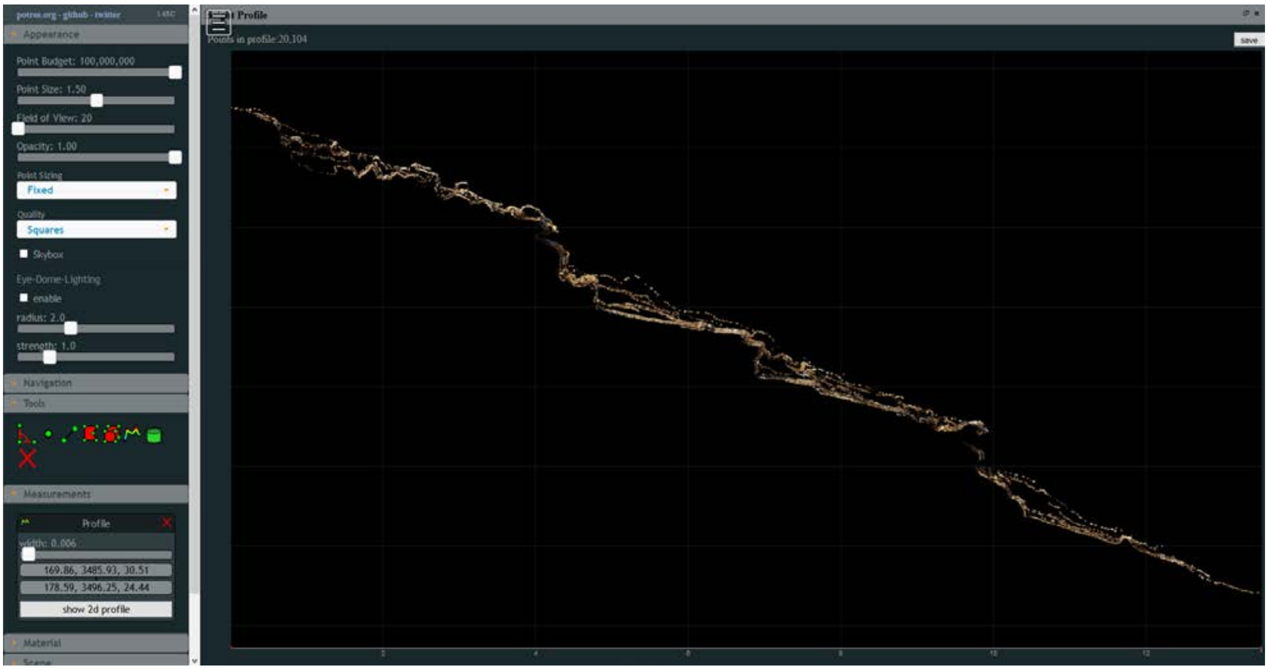

Figure 8. Trench L, deposits sequence

traditional WebGL enabled browsers, is built over an open-source viewer, allowing for the interactive streaming of point cloud. The digital platform is based on the objective of creating an open and scalable system which is able to display different kinds of 3D objects in the same web environment (Figure 7). Through the proposed database architecture, high-resolution 3D models consisting of millions of points and RGB values are available online via the open source WebGL based Potree viewer (Schutz and Wimmer, 2015). Potree is a point-based rendering solution specifically developed for visualizing large point clouds using standard web-based technologies. It is capable of easily providing a responsible interactive viewer that only requires a traditional web browser (WebGL enabled), freeing the user

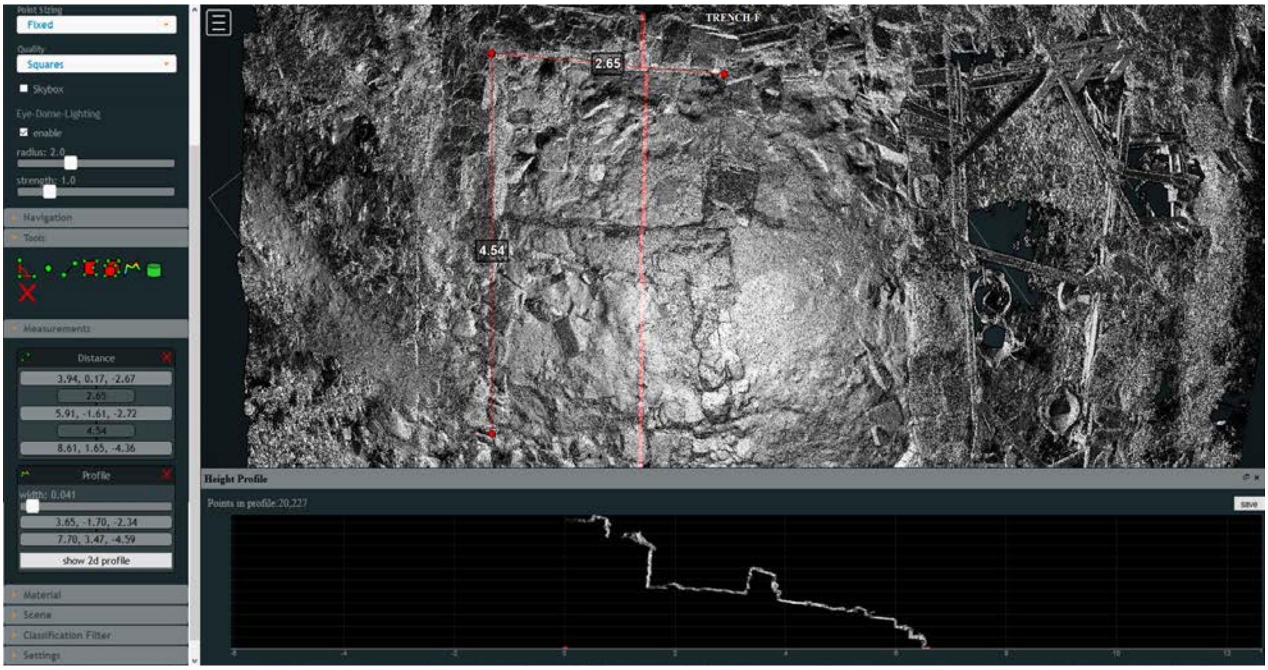

Figure 9. Web visualization system

from any configuration issues or specific software. Potree point cloud files are encoded in an octree data structure using a dedicated converter (Schutz, 2018) guaranteeing a high level of content protection and security.

The selected viewer features the ability to:

- visualize 3D point clouds online; measure distance, compute volumes and areas;
- extract, visualize and download sections;
- link with external resources (metadata) through dedicated hotspots located on the 3D interactive point cloud.

A virtual excavation diary is available according with the following multi-scale data structure:

the first level of information is represented by the Digital Elevation Model (DEM) acquired from an aerial platform covering the entire island of Daskhalio; at ground level, each trench is visible as a layer-to-layer 3D documentation, allowing to switch among deposits and analyse their morphological features and relationships (figure 8);

finally, a 3D multi-temporal (yearly) laser scanning model of each trench is available (Figure 9).

All the different levels of information are available through interactive hot-posts located in the 3D virtual environment.

Conclusion

This work proposed a comprehensive and interactive tool for the visualization of the excavation of the rocky islet of Dhaskalio, exploiting an open-source web-based platform composed of different level of details (LODs). First of all, a pyramidal multi-level and multi-sensor 3D modelling strategy through the use of different kind of active and passive sensors has been illustrated.

Thereafter, the paper focused on the visualization platform which was built to allow the final users, belonging either to the scientific community or a public audience, to analyse the 3D environment from a landscape to a layer-by layer perspective. The proposed technologies have shown the reliability of data streaming of high-resolution three-dimensional models, providing smooth online interaction and visualization.

Since the island of Keros and Daskhalio have been deemed inaccessible due to conservation and scientific issues, the proposed web system could allow users to access and virtually experience sites otherwise impossible to visit in the near future.

Future Works

Future work will integrate this output with the photogrammetry models, allowing a user to virtually re-excavate the site by visualising contexts in 3D, the stratigraphic relationships, and the sequence of context deposition (and removal). It further envisaged that as the GIS platform develops 3D models may ultimately be integrated within it.

References

Abate, D, Sturdy-Colls, C 2018 A multi-level and multi-sensor documentation approach of the Treblinka extermination and labor camps, *Journal of Cultural Heritage* 34 (6): 129-135, https://doi.org/10.1016/j.culher.2018.04.012.

Bonora, V, Tucci, G, and Vaccaro, V 2005 3D data fusion and multi-resolution approach for a new survey aimed to a complete model of Rucellai's chapel by Leon Battista Alberti in Florence, In: Dequal, S (ed.) *Proc. of CIPA XX Int. Symposium*, Turin.

Cantoro, G 2017 Ground and aerial digital documentation of cultural heritage: providing tools for 3D exploitation of archaeological data. In: *Int. Arch. Photogrammetry Remote Sens. Spat. Info. Sci. XLII-2/W3 - 3D Virtual Reconstruction and Visualization of Complex Architectures, 1–3 March 2017,* Nafplio, Greece. https://doi.org/10.5194/isprs-archives-XLII-2-W3-141-2017

El-Hakim, S, Remondino, F, andVoltolini, F 2008 Integrating techniques for detail and photo-realistic 3D modelling of castles, *GIM Int* 22 (3), pp. 21–25.

Faka, M, Christodoulou, S, Abate, D, Ioannou, C, and Hermon, S 2017 A 3D based approach to the architectural study of the roman bath at the sanctuary of Apollo Hylates (Kourion, Cyprus), *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, IV-2-W2: 91-98. https://doi.org/10.5194/isprs-annals-IV-2-W2-91-2017.

Guidi, G, Remondino, F, Russo, M, Menna, F, and Rizzi, A 2008 3D modeling of large and complex site using multi-sensor integration and multi-resolution data, in: Ashley, M., Hermon, S., Proença, A., Rodriguez-Echavarria, K. (eds.) *Proc. 9th Int. Symposium on virtual reality, archaeology and cultural heritage (VAST)*, Braga, Portugal, 2008, pp. 85–92.

Guidi, G, Remondino, F, Russo, M, Menna, F, Rizzi, A, and Ercoli, S 2009 A multi-resolution methodology for the 3D modeling of large and complex archaeological areas, *Int. J. Architect. Comput.* 7 (1), pp. 39–55.

Gruen, A, Remondino, F, and Zhang, L 2005 The Bamiyan project: multi-resolution image-based modelling, *Record. Model. Vis. Cult. Herit* 18, pp. 45–54 (ISBN 0 415 39208 X).

Hermon, S, Vico, L, Depalmas, A, and Atzeni, I 2017 A 3D approach to the archaeological study of the built remains at the Santa Cristina well sanctuary, Sardinia, Italy, *Digital Applications in Archaeology and Cultural Heritage* 6 (Sept.): 4-9. http://dx.doi.org/10.1016/j.daach.2017.08.002.

Mills, J, Andrews, D 2011 *3D Laser Scanning for Heritage. Advice and guidance to users on laser scanning in archaeology and architecture.* (2nd ed.) Swindon: Historic England Publishing.

Patias, P, Georgoula, O, Georgiadis, C, Stamnas, A, and Tassopoulou, M 2009 Photogrammetric documentation and digital representation of excavations at Keros island in the Cyclades. *ISPRS Archives Vol. XXXVIII-3/W8, XXII CIPA Symposium*, Kyoto, Japan.

Ramos, M, and Remondino, F 2015 Data fusion in cultural heritage – A Review. *ISPRS archives of the photogrammetry, Remote Sens. Spat. Info. Sci.* XL–5/W7, pp. 359–363 (25th CIPA Symposium, Taipei, Taiwan).

Remondino, F, Gruen, A, von Schwerin, J, Eisenbeiss, H, Rizzi, A, Sauerbier, M, and Richards-Rissetto, H 2009 Multi-sensors 3D documentation of the Maya site of Copan, In: *Proc. of 22nd CIPA Symposium*, 11–15 Oct, Kyoto, Japan, 2009.

Remondino, F, Spera, M G, Nocerino, E, Menna, F, and Nex, F 2014 State of the art in high density image matching. *The Photogrammetric Record* 29 (146): 144-166, DOI: 10.1111/phor.12063.

Renfrew, C, Philaniotou, O, Brodie, N, Gavalas, G, Margaritis, E, French, C, and Sotirakopoulou, P 2007 Keros: Dhaskalio and Kavos, early Cycladic Stronghold and Ritual Centre. Preliminary Report of 2006 and 2007 seasons. *Annual of the British School at Athens* 102: 103-136.

Renfrew, C, Philaniotou, O, Brodie, N, and Gavalas, G 2009 The Early Cycladic settlement at Dhaskalio, Keros: Preliminary report of the 2008 excavation season. *Annual of the British School at Athens* 104: 27-47.

Renfrew, C, Boyd, M, and Ramsey, C B 2012 The oldest maritime sanctuary? Dating the sanctuary at Keros and the Cycladic Early Bronze Age. *Antiquity* 86 (331): 144-160.

Renfrew, C, Philaniotou, O, Brodie, N, Gavalas G, and Boyd, M J (eds.) 2013 *The settlement at Dhaskalio.* McDonald Institute for Archaeological Research, University of Cambridge.

Schutz, M and Wimmer, M 2015 Rendering large point clouds in web browsers, in: *Proc. 19th CESCG*, pp. 83–90.

Schutz, M 2014 *PotreeConverter – uniform partitioning of point cloud data into an octree* (Available at: http://potree.org/downloads/ converter documentation. pdf), [Last accessed: 10 August 2018].al models, providing smooth online interaction and visualization.

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Viability of Production and Implementation of Retrospective Photogrammetry in Archaeology

Colin Wallace
Geography and Environm. Management
University of Waterloo, Ontario
colin@uwaterloo.ca

Dorina Moullou
Ephorate of Antiquities of East Attica
Hellenic Ministry of Culture and Sports, Athens
tmoullou@culture.gr

Abstract

Retrospective photogrammetry is a novel approach to producing fully functional three-dimensional models using archival photographs, plans and drawings augmented with contemporary photogrammetry and surveying. This paper addresses the advantages as well as the difficulties in using retrospective photogrammetry and examines how the results can be put to use for further research, preservation, restoration, monitoring rates of deterioration and presentation to the public. We examine the approach to retrospective photogrammetry from the perspective of both the photogrammetrist and the end user (ie. researcher, scholar or authority responsible for using or disseminating the resulting data). From the perspective of the photogrammetrist it is the nature and quality of the archival data that is of concern. Does the archival material meet the needs of 3D modeling and will the resulting models meet the needs of the end user? The end user is concerned with being able to store, access and utilize the results constructively. An impressive 3D model without detail or metrics is of little use apart from public presentation. We explain why the end user's goals must be addressed clearly prior to commencing the project.
We will look at examples from the Athenian Agora and Ancient Corinth to illustrate the methods required, limitations experienced and opportunities made possible with the resulting products.

Keywords: Retrospective Photogrammetry, Photogrammetry, 3D Modelling, Archival Photographs, Archaeology

Introduction

Retrospective Photogrammetry is a method of producing metrically accurate three dimensional models by using archival photographs, drawings and data (Wallace 2017). When applied to archaeological sites and monuments, the resulting models can be used to aid in conservation, rehabilitation and restoration of sites as well as aiding in ability to study these excavations as they were and in some cases, examine sites that no longer exist (Gruen et al. 2002, Falkingham et al. 2014, Lallensack et al. 2015,Wilson et al. 2016, Wallace 2017, Maiwald et al 2017, Zawieska et al. 2017, Wolter 2018, Condorelli and Rinaudo 2018, Wallace 2021, Panagiotopoulou et al. 2023). In this paper we examine both the viability of retrospective photogrammetry and whether there are justifiable benefits to it. We will do so using examples from the Athenian Agora and Ancient Corinth.

Retrospective Models

Fountain of the Lamps

One of the first examples to be examined has been the fountain of the lamps in Ancient Corinth. First discovered in 1968 by James Wiseman, the fountain of the lamps was a rich, robust archaeological site with a main swimming pool and covered bath areas built into

Figure 1. Fountain of the Lamps 3D modelling in 2012

the bedrock and supplied by natural springs. While the site was able to survive intact since the late third century b.c.(Wiseman 1970), once excavated, deterioration began. Currently, the bath areas have collapsed and the pool area is inundated with reeds and fig trees. Walls have fallen and the entire area cannot be studied safely in its present state. Wiseman found that "other connecting structures, almost certainly including a fountainhouse, were in use during the late third century b. c. and into the next century" (Wiseman 1970). He, as an end user of photogrammetry, has expressed a desire to re-examine certain aspects of the site that are no longer available. We have all photographed elements and events at a time when we felt we had fully documented them only to find afterwards that there are gaps in our recording. Through retrospective photogrammetry, aspects of the site have been able to be recreated and can be re-examined from perspectives that were not initially recorded.

Omega House

Omega House is a Roman villa built in the fourth century A.D. and modified through the sixth century A.D. The building is thought to be the home of the last school of philosophy in ancient Greece (Camp 1989). The structure was excavated in the late 1960's and early 1970's by John Camp. The site is not currently accessible and some aspects are backfilled or deteriorating due to exposure. There is a desire in the Hellenic Ministry of Culture and Sports to conserve and restore Omega house which has significant water features, mosaics and architecture. With that aim in mind, Omega House was modelled three dimensionally in its current state as well as being modelled using archival photographs taken when it was first excavated (Wallace et al 2017). The resulting models are being used to determine both the level of deterioration and the viability of restoration. In this case, with detailed modelling we are able to examine individual walls and work with engineers to move forward in the preservation of this important historic site.

These two examples show that there are considerable differences in what they end user's expectations and uses are for the photogrammetric models. What the end user needs depending on which of these purpos-

Figure 2. Fountain of the Lamps 3D modelling as it was in 1972

es is intended, determines the photogrammetrist's approach to the modeling and in their assessment of available materials and whether those goals can be achieved.

Currently it is acknowledged that having a photogrammetric record of a site, monument or excavation is of great importance (Ragia and Moullou 2023). More site permits, in Greece for example, are now requiring such documentation. One result is that each of these projects benefits from having an infinite number of measurements and images available through the photogrammetric 3D models produced.

Previous, much older archaeological projects did not benefit from such technology and so have a finite number of records in their data sets. Metric data have been collected for CH documentation using digital photogrammetry and laser scanning methods and techniques, since the 1990s (Adel Haddad 2013). Through retrospective photogrammetry we are able to expand those analogue data sets to a level almost comparable to if those sites were excavated today.

Where retrospective photogrammetry comes into its element is when there has been significant deterioration since the time of excavation which can include destruction due to natural disasters, erosion, pillaging, encroachment of wildlife and plant life or even backfilling and removal of features in rescue archaeology (when a road or other civic project takes precedent).

What the previous examples illustrate is that the needs of the end user can be quite varied and that there needs to be a commnuncation between the photogrammetrist and the end user to determine that the outcome is the most productive and useable.

Figure 3. Omega house modelled from 1972 photographs

What the Photogrammetrist Needs

Access

One of the most difficult steps in the whole retrospective photogrammetry process is in ascertaining what photographs actually exist of a site and in what ways can they be accessed. While an official archive such

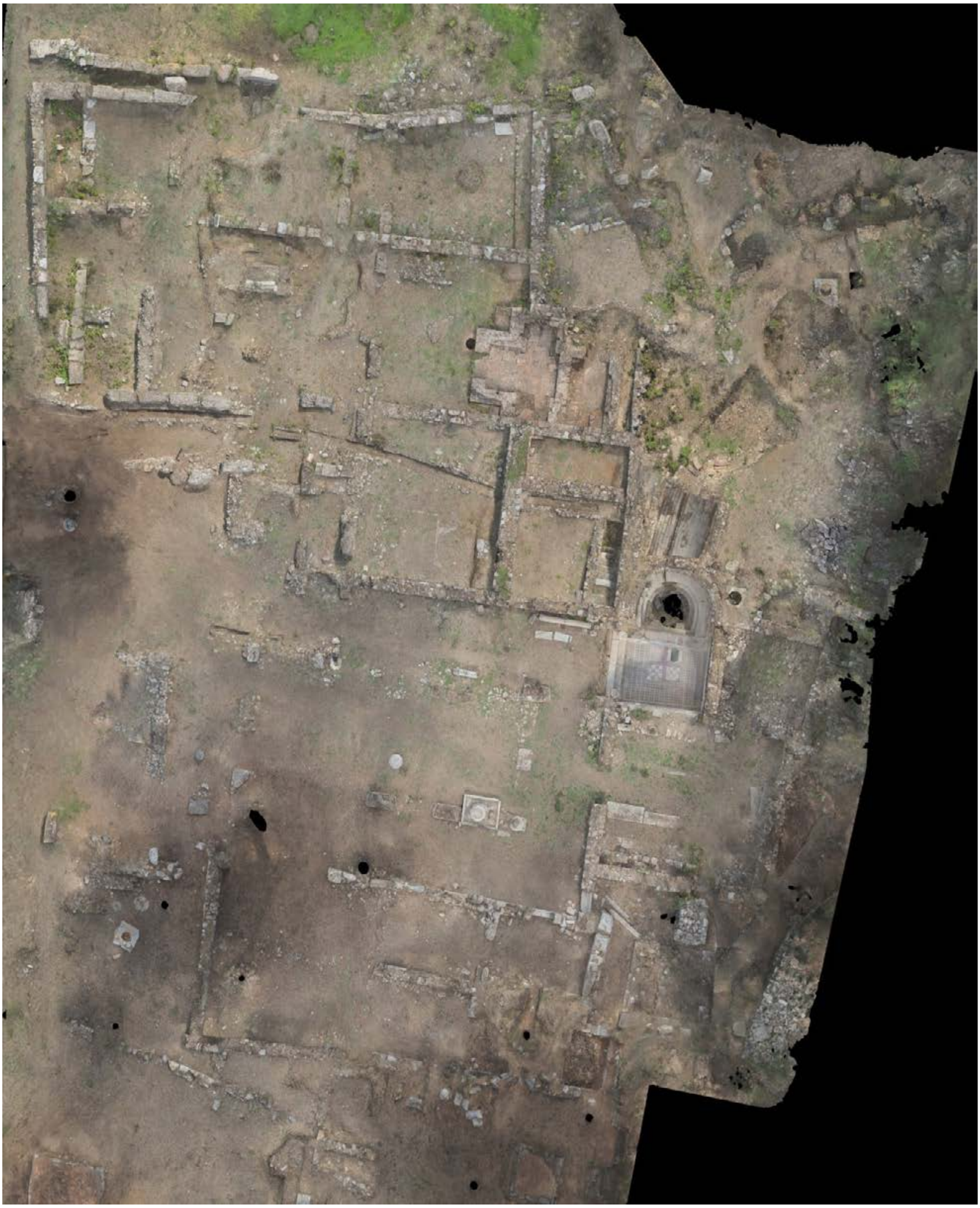

Figure 4. Omega House as modelled in 2017

as that of the American School of Classical Studies in Athens can be accessible online, one of the first problems to be encountered is data entry and organization. For example, a particular structure may be recorded with one name but as excavation continues that name may change. In order for the database to be able to access the right records in notebooks, the original name remains with the earlier records so in order to search for the entire listing of photos, all of those names need to be known. For example, Omega House in the Athenian Agora can also be found as Roman House H, House C and Philosophical School C.

What is needed for a viable selection of photographs? As with any photogrammetry, a comprehensive collection of photographs with a suitable overlap between them is desired. The impediment to this is that we cannot go back in time and take missing pictures, also in cases where no significant changes have taken place over time, modern photographs, treated suitably can be added. Depending on the end user's needs, a site without full comprehensive coverage might work (Wallace et al. 2017).

Once an eligible collection of photographs has been identified, there is the matter of access. While many photographs are available through online archives, determining what else is available is vital. Accessing and scanning original negatives (film or glass) reduces errors considerably by removing the lens error of the enlarger lens, removing extra grain in prints and making sure that scans are done at a high resolution using the same scanner (and thus the same scanner lens). Our work has concentrated on reducing all aspects of error in this process (Wallace 2022).

What the End User Needs

In an archaeological project, the end user is not only the archaeologist. Since it is an interdisciplinary project, it involves researchers of almost all fields: archaeologists, architects, civil engineers, surveyors, specialists in photogrammetry, chemical engineers, conservators etc). Therefore the end product must meet the needs of all the scholars involved.

The end user needs an accurate textured model. There are two forms of accuracy. An aesthetic accuracy that can be presented to the public, and metric accuracy to be used in scholarly research, conservation, and restoration.

Aesthetic accuracy means that the retrospective model presented is convincing in its appearance in what it represents of the site as it was previously. This can, on paper, be a paradox because a visually accurate model can have a large metric error in its points and pixels. Agisoft Photoscan, the author's software choice due to its ability to process uncalibrated photographs, assigns accuracy results but those results are a comparison of what the end result is and what the software expected. The only true way to measure accuracy in a model is to take known, real life measurements and then take those same measurements within the model. In the case of Omega House in the Athenian Agora, measurements of distances of thirty to forty metres vary between reality and model at 20 to 30 centimeters error. Given that the resolution and ability to pinpoint measuring points constitutes at least that much difference the accuracy of the modeling is acceptable (Wallace et al. 2017, Panagiotopoulou et al. 2023).

The idea that photogrammetry could be used to attain accurate measurements that could be used for archaeological restoration is not new. In 1961 E.H.Thompson, writing about the restoration of Castle Howard noted that "Important monuments have been damaged in the past and restored or even entirely reconstructed with the help of photographs not taken for photogrammetric purposes." (Thompson 1961). Granted, these "reconstructions" were essentially ascertaining the measurements and locations of two dimensional elements but they support a longstanding idea that there is significant stored data in archival photographs. The photographs in the case of Castle Howard were taken in the 1920's and 1940's.

For the aesthetic modeling, end users lean towards smaller file sizes and the ability to present on multiple platforms and with limited equipment abilities and storage. Budgetary constraints and existing equipment abilities need to be taken into account and planned for by the photogrammetrist at this stage or the result can become unwieldy and unusable for the end user. For example, end products intended for the Hellenic Ministry of Culture and Sports, depending on the facility or subgroup, can be limited by existing resources as a result of budgetary constraints. The resulting product must be suitably scaled with regard the abilities of the existing infrastructure. For example, on slower machines, attempting to present the model to the client using Adobe 3D PDF or even the native environment in Agisoft Photoscan on a slower machine can result in jerky motion or the inability to present the object impressively. Viewer such as open 3D model viewer and Microsoft Mixed reality viewer can allow an impressive and flexible display of the model. For presentation to the public, Sketchfab allows a versatile and easily accessible means of sharing results with the non academics.

For Virtual Reality presentation purposes it is best to establish a budget beforehand and tailor the modeling /VR environment to suit the budgetary constraints of the client. Spatial constraints must also be considered when choosing the means by which the VR is to be presented. In some cases due to publishing rights, etc., the client may wish the VR to be only available on site. In these situations the number of viewers at one time can also be a consideration. In other cases the client may want their VR environment to reach the largest possible audience and choose online availability to do so.

For the geometric documentation of monuments and sites high accuracy and large scale end products are needed. However, this does not guarantee that everyone involved will be able to use it (Moullou and Mavromati 2007). The final output must have all necessary information to avoid misinterpretation. This is why the end product must be explicitly determined a priori, based on strictly defined needs, specified together by the end users and the photogrammetrist.

Drawings done on a site in the past, while attempting to be as objective as possible, are recorded with the subjective eye. Nuances that may have seemed important at the time can be over concentrated on while other less interesting aspects can be underrepresented (Wallace 2017). Retrospective photogrammetry can allow the contemporary researcher to re-examine those nuances and produce new more objective data.

Conclusions

Photogrammetric documentation of archaeological sites has rapidly and thankfully accelerated in recent years. When such documentation first became available in an affordable manner, many in the archaeological community were excited that it could be done but fewer questioned what could be done with it. For some of them an amusing model was created and was tucked away when it came to publications, apart from some screen shots. However, those who have come to understand the true potential of the technology have realized the amount of deep data that the models can provide for scholars to examine and quantify elements within the models.

Beyond the micro-examination of models, the amount of contained data within modelling has been realized by those focused on entire sites or monuments. The reconstruction of Notre Dame, Paris in as close to its original form would not be possible without the efforts of 3D modellers, not only for identifying the form of the original construction but also for test fitting elements before physical reconstruction (De Luca 2020)..

The ability to capture sites and monuments as they currently are or, within the context of this paper, as they were when first photographed, allows us to revisit and even reconstruct these aspects of cultural heritage with confidence and relative accuracy.

The effective completion of this effort is impossible without the creative collaboration of experts from various disciplines of study. The attempt to create a successful photogrammetric model, which is directly dependent on the use of the final product, necessitates rigorous preparation, research, and a lengthy collaborative effort of all relevant specialties.

Reference

Adel Haddad, N 2013 From Hand Survey to 3D Laser Scanning: A Discussion for Non-Technical Users of Heritage Documentation. *Conservation and Management of Archaeological Sites*, 15(2), 213–226.

Camp, J M II 1989 *The philosophical Schools of Roman Athens*. Bulletin Supplement (University of London, Institute of Classical Studies), no. 55 (1989): 50-55. http://www.jstor.org/stable/43768502

Condorelli, F and Rinaudo, F 2018 Cultural Heritage Reconstruction from Historical Photographs and Videos, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2: 259–265, https://doi.org/10.5194/isprs-archives-XLII-2-259-2018

De Luca, L 2020 Towards the Semantic-aware 3D-Digitisation of Architectural Heritage: The "Notre-Dame de Paris" Digital Twin Project, SUMAC'20. In: Gouet-Brunet, V, Khokhlova, M, Kosti, R, Chen, L, Yin, X (eds.): *Proceedings of the 2nd Workshop on Structuring and Understanding of Multimedia Heritage Contents, Seattle*, WA, USA, 12–16 October 2020; pp. 3–4. DOI: https://doi.org/10.1145/3423323.3423415

Falkingham, P L, Bates, K T and Farlow, J O 2014 Historical photogrammetry: Bird's Paluxy River dinosaur chase sequence digitally reconstructed as it was prior to excavation 70 years ago. *PLoS ONE* 9(4): e93247. https://doi.org/10.1371/journal.pone.0093247

Gruen, A Remondino, F and Li, Z 2002 Reconstruction of the Great Buddha of Bamiyan Afghanistan. *Int. Arch. Photogramm. Remote Sens.* 34(5): 363–368

Lallensack, J N, Sander, P M, Knötschke, N and Wings, O 2015 Dinosaur tracks from the Langenberg Quarry (Late Jurassic, Germany) reconstructed with historical photogrammetry: evidence for large theropods soon after insular dwarfism. *Palaeontologia Electronica*, 18(2), p. 31A.

Maiwald F, Vietze, T, Schneider, D, Henze, F, Münster, S, and Niebling, F 2017 Photogrammetric analysis of historical image repositories for virtual reconstruction in the field of digital humanities. In: Aguilera, D, Georgopoulos, A, Kersten, T, Remondino, F, and Stathopoulou, E. (eds.) *The international archives of the photogrammetry, remote sensing and spatial information sciences, volume XLII-2/W3. Proceedings of the 3D virtual reconstruction and visualization of complex architectures*. 1–3 March 2017, Nafplio.

Moullou, D, and Mavromati, D 2007 Topographic and photogrammetric recording of the Acropolis of Athens. In: Int. Com. of Archit.Photogram., and Georgopoulos, A (eds.) *Proceedings of XXI international CIPA symposium*, 1–6 October, Athens, pp 515–520.

Panagiotopoulou, A, Wallace, C A B, Ragia, L, Moullou, D 2023 Change Detection between Retrospective and Contemporary 3D Models of the Omega House at the Athenian Agora. *Heritage* (6) pp. 1645-1679, https://doi.org/10.3390/heritage6020088

Ragia, L, and Moullou, D (eds.) 2023 Special Issue "Photogrammetry, Remote Sensing and GIS for Built Heritage" *Heritage* (6) https://www.mdpi.com/journal/heritage/special_issues/51BG0762YV

Thompson, E H 1962 Photogrammetry in the restoration of Castle Howard. *The Photogrammetric Record*, 4: 94-119. doi:10.1111/j.1477-9730.1962.tb00334.x

Wallace, C 2017 Retrospective Photogrammetry in Greek Archaeology. *Studies in Digital Heritage*, 1(2): 607-626. https://doi.org/https://doi.org/10.14434/sdh.v1i2.23251

Wallace, C 2021 Retrospective Photogrammetry: 'Building a Time Machine'. In: D'Amico, S, and Venuti, V (eds.) *Handbook of cultural heritage analysis*, 1st ed. Springer, pp. 1643–1676.

Wallace, C 2022 Refinement of retrospective photogrammetry: an approach to 3D modeling of archaeological sites using archival data. *Archaeol. Anthropol. Sci.* 14, 192. https://doi.org/10.1007/s12520-022-01632-0

Wallace, C, Dedík, L, Minaroviech, J, Moullou, D 2017 3D Modeling and Virtual Access of Omega House in the Athenian Agora. In: *Proceedings of the 22nd International Conference on Cultural Heritage and New Technologies*, Vienna, Austria, 10–12 November 2017.

Wilson T, Miles H C, Labrosse, F, Tiddeman, B, Roberts, J C 2016 Historical records, archives and photogrammetry. *Hist. Environ.* 7(1):25–42. https://doi.org/10.1080/17567505.2016.1142696

Wiseman, J 1970 The Fountain of the Lamps, *Archaeology* 23 (2): 130-137. http://www.jstor.org/stable/41658792

Wolter T 2018 Reconstructing excavations? Photogrammetry on 1980's photos. *Abstracts of the CAA Conference 2018, Tuebingen, Mar. 19-23, 2018*, p. 60.

Zawieska D, Markiewicz JS, Kopiasz J, Tazbir J, Tobiasz A 2017 3D modelling of the Lusatian borough in Biskupin using archival data. *Int Arch Photogramm Remote Sens Spat Inf Sci* XLII-2/W3:665–669. https://doi.org/10.5194/isprs-archives-XLII-2-W3-665-2017

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2018

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Powerful Pictures: Uncovering Data in Aerial Photogrammetric Imagery

Scott Ure
Department of Anthropology
Brigham Young University
scott_ure@byu.edu

Abstract

Unmanned aerial systems (UAS) are useful tools for many archaeologist; however, the data within the images captured by these systems is frequently underutilized. This paper discusses the benefits of extracting information embedded in aerial photogrammetric images and using them to improve mapping and documentation of archaeological sites. This paper offers three case studies to provide examples of how aerial photogrammetric imagery can help identify features and patterns not always recognizable from the ground or from standard aerial images.

Keywords: UAS, Photogrammetry, Structure-from-motion, Aerial imagery, Mapping

Introduction

Unmanned Aerial Systems are capable of providing stunning aerial imagery, however these images are often underutilized. In many cases photogrammetric images are used to generate orthomosaics, but often never mature beyond "pretty pictures". Advances in structure from motion (SfM) photogrammetric modeling and geographic information systems offer tools to harvest geospatially relevant and informative data from low altitude aerial imagery. This paper discusses methods and benefits for using aerial photogrammetry to accurately map large-scale sites, identify obscured archaeological features, and measure three-dimensional space. Conclusions are formulated from aerial photogrammetric data captured at three archaeological sites: the Ad Deir plateau in Petra, Jordan; the adobe-walled city of Paquimé in Chihuahua, México; and the Aztatlán site of Santo Domingo located in the coastal plain of Jalisco, México.

This paper specifically discuss ways structure from motion photogrammetric imagery are used to analyze archaeological sites. Examples include digital surface models (DSMs) used for geospatial studies, producing topographic maps with custom contour intervals to update outdated or non-existent maps, creating animations for documentaries and visualization used for public outreach, and generating georectified orthomosaics that integrate with traditional survey data and geospatial databases in basemap formats. Results from the case studies presented in this paper include the production of a topographic map for the Ad Deir plateau, the identification of architectural alignments at the Santo Domingo site, and defining unexcavated regions in Paquimé for future research. This paper concludes that utilizing the data within aerial photogrammetric imagery offers access to a wealth of informative data that can be used to uncover additional and often unseen patterns and information at archaeological sites.

Definitions

Photogrammetry

The concepts and practice of photogrammetry can be traced back several centuries to early studies in perspective, projection, and the development of photography (CPT 2008:1). There are many individuals who have contributed to the modern practice of photogrammetry, but these achievements rest on the shoulders of scientists and artists alike. Names such as Di Vinci, Lambert, and Dürer are on a long list that built the foundation for photogrammetric imagery. Anton Schenk (2005:3) suggests that there is "no universally accepted definition of photogrammetry." He does, however, offer his own definition of photogrammetry as "the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information" (Schenk 2005:3). CAST (2018) defines digital photogrammetry as "a well-established technique for acquiring dense 3D geometric information for real-world objects from stereoscopic image overlap and has been shown to have extensive applications in a variety of fields."

Photogrammetry targets can include anything from planets, mountain ranges, and buildings to the human body, industrial parts, and even small items such as coins, ceramic sherds, and any number of things whose shape can be recorded via a sensor, but typically with a camera (Schenk 2005:4). There are essentially two types of digital photogrammetry today: aerial and terrestrial or close-range. Aerial photogrammetry involves capturing imagery from an aerial platform or vehicle, but typically from an airplane or UAV. Close-range photogrammetry is usually performed at ground level and at a small scale using a variety of cameras, It is most successful using higher resolution, full-frame cameras with a fixed focal length lens. Advances in camera quality and software applications used to process the images are making close-range photogrammetry very popular. The same is true with aerial photogrammetry as UAVs are growing in capability and usability. In many instances, the terms photogrammetry and structure-from-motion are used interchangeably today, but there are some technical differences as noted below.

Structure-from-Motion (SfM)

Matthew Westoby et al. (2012:301) state that structure-from-motion has it origins in the computer vision community of the early 1990s and is based off algorithms developed in the 1980s. Structure-from-Motion (SfM) "operates under the same basic tenets as stereoscopic photogrammetry, namely that 3-D structure can be resolved from a series of overlapping, offset images" (Westoby et al. 2012:301). Structure-from-motion differs from traditional photogrammetry, however, in that it does not require previously established camera positions and orientation, nor does it necessarily need known control points. It can calculate three dimensional structure based on a set of highly overlapped and offset images (Westoby 2012:301). Westoby et al. (2012:301) explain that structure-from-motion creates the camera positions and scene geometry simultaneously through the "automatic identification of matching features in multiple images." Although structure-from-motion is capable of constructing structure without reference points, results are often improved by placing physical targets, such as high-contrast ground control points, before photographs are captured (Westoby et al. 2012:301).

In practice, the object in question must be photographed from multiple angles with a high degree of overlap, thus structure is created from the movement of the sensor or camera around the target. Natan Micheletti, Jim Chandler and Stuart Lane (2015:2) explain that the "scale invariant feature transform" algorithm is used to identify "common feature points across the image set, sufficient to establish the spatial relationships between the original image locations in an arbitrary 3-D coordinate system." The data is then processed through a "sparse bundle adjustment" which transforms the measured coordinates into a sparse 3-D point cloud (Micheletti, Chandler & Lane 2015:2). The sparse point cloud is then used to create a dense point cloud using "multi-view stereo techniques" (Micheletti, Chandler & Lane 2015:2).

Generating the dense point cloud requires distinct variation in texture and can be sensitive to lighting conditions. Two different SfM applications were used in the case studies for this paper: Pix4D's Pix4Dmapper and Agisoft Photoscan Pro. Both have similar capabilities which were used to generate a variety of datasets in all three case studies. The following sections discuss the power of SfM photogrammetry to extract informative and actionable information beyond a static aerial image.

Figure 1. Map showing the location of Petra in southwest Jordan.

Case Studies

Ad Deir Plateau, Petra, Jordan

In early 2013, faculty, staff, and students from Brigham Young University (BYU) planned a pedestrian archaeological survey of a very remote portion of the UNESCO World Heritage site of Petra, Jordan known as the Ad Deir Plateau (Figure 1). The plateau is located 1.5 kilometers northwest of the ancient Nabatean city center of Petra in the rugged desert mountains. The archaeological features at Ad Deir generally date to the first century A.D. The Ad Deir Plateau is accessed using a trail that starts in the Petra city center and winds through slots canyons before reaching the top of the plateau. Little is understood about why and how the Nabateans used this mountain top to build some of the larger structures in Petra. Archaeological features found on top of the Ad Deir plateau include massive barrel-vault covered cisterns, rock cut tombs, pools, and complex water channels. The "Monastery," a large monumental structure and centerpiece for the entire area, stands about 45 meters above ground and measures approximately 50 meters in width (Figure 2).

Accurate topographic maps for the Ad Deir plateau are rare at best. Generating an accurate topographic map of the region was a critical first step for a successful archaeological pedestrian survey and documentation of the plateau. Creating this map presented a daunting task due to the geographic size and extremely rugged terrain. Traditional terrestrial topographic surveying methods were not possible with the time and resources available, and the extreme terrain would have placed the surveying crew in exposed locations. Hiring a pilot with the necessary plane, aerial camera, and capability to process the images was also well outside the project budget.

In order to document the plateau and all the associated archaeological features BYU archaeologists used a fixed-wing UAS made by Gatewing and Trim-

Figure 2. Photo of the Ad Deir Monument located on the Ad Deir Plateau in Petra, Jordan. Photo courtesy of Joseph Bryce.

ble. This survey grade UAS, called the X100, was used to collect aerial imagery that was later used to generate georeferenced imagery that provided the foundation for various analyses and structure from motion (SfM) modeling. The X100 is fully autonomous, although users do have the ability to take control of the aircraft in emergency situations. The unmanned aerial vehicle (UAV) portion of the system is launched via a catapult which propels the aircraft into the air at a high rate of speed (Figure 3). The X100 lands on underside of the fuselage causing the folding propellers to fold backward to avoid damage. The X100 is made of expanded polypropylene (EPP) foam which is reinforced by a carbon fiber structure. It uses one lithium polymer battery that can power the entire aircraft and its associated systems for 45 minutes. The X100 has a 1 meter wingspan and can fly up to 80 kilometers per hour with an 2500 meter maximum ceiling and a 53 kilometer range. The camera is mounted inside the flight frame underneath the X100 and produces 10 mega pixel images which can provide a ground sampling distance (GSD) range from 3.3 to 25 cm.

A series of six ground control points (GCPs) were placed across the plateau prior to flight, and their positions were recorded using a Trimble GeoXH GPS with a tornado antenna. The GCPs were used to refine georeferencing during post processing. The flight over Ad Deir took approximately 30 minutes and covered a square kilometer. The X100 was launched and landed approximately 2.5 kilometers northeast of the plateau in one of the only open, flat fields in the area. The UAV flew at nearly 300 meters in altitude and captured 285 3648 x 2736 pixel photographs during 16 north-south transects. The resulting GSD was 11 cm per pixel which provided good resolution for identifying large architectural features. Smaller archaeological features were not as easily recognized. The images collected by the X100 were processed using Pix4Dmapper made by the Swiss company Pix4D.

An orthomosaic, survey grid, DSM, and contour

Figure 3. Photo of the Gatewing X100 fixed-wing UAS and catapult prior to take-off. The launch area was located approximately 2.5 kilometers northeast of the Ad Deir Plateau in the Al Beidha region. Photo courtesy of Bruce Allardice.

lines (5 meter interval) were generated from the captured images using Pix4Dmapper (Figure 4). These datasets were extremely valuable for planning the pedestrian survey across the plateau. The orthomosaic was imported into Avenza's MAPublisher which was used to create a virtual survey grid across the site. Each grid represents a 50 by 50 meter survey area on the ground. This grid was uploaded to a GPS and used by surveyors to identify their locations within a given survey block. The pedestrian survey covered 40 acres (16 hectares) and documented 533 separate archaeological features.

The Ad-Deir survey would not have been nearly as successful without the aid of the X100 UAS. The aerial orthomosaic allowed the survey team to more accurately assess the terrain and establish a plan to efficiently survey a very rugged location containing numerous archaeological features. In addition, the X100 was able to photograph, in high resolution, nearly a square kilometer of terrain which would have been too costly, both in time and accuracy, to document with a total station, GPS, or traditional aircraft. The data produced from the images acquired from the flight allowed for the generation of a very accurate topographic map, orthomosaic, DSM, and animations used in a documentary. These datasets were combined with linear, point, and polygonal GPS data collected during the pedestrian survey which resulted in a map showing the position and relationship between the numerous archaeological features, as well as their placement on the landscape. Several previously unmapped architectural features located on top of the steep, high cliffs northwest of the Monastery were also observed during image analysis.

Paquimé, Chihuahua, México

The UNESCO World Heritage site of Paquimé is located in the Chihuahuan desert of northern México (Figure 5). Charles Di Peso (1974:370) noted that Paquimé reached its zenith around

A.D. 1300 and measures approximately 88 acres or 36 hectares in size. Paquimé was built around a central polity with ceremonial mounds, multi-level structures, and Mesoamerican- style ball courts. The city was built of massive adobe walls and stone masonry and represents a collaborative organization

Figure 4. Orthomosaic generated by Pix4Dmapper from the images captured during the X100 flight. Contour lines were produced from a digital elevation model also created from the orthomosaic. The contour lines are shown superimposed over the orthomosaic.

Figure 5. Map showing the location of Paquimé in northern México.

of labor. Di Peso (1974:370) elaborates that Paquimé was built by a "massive labor force, which, operating under the strict control of a few individuals, produced a telltale pattern of wall abutments, underground plaza drain systems, formalized plazas, public entries, subterranean ceremonial structures, and staggered outer wall designs." Paquimé was among the largest, socially complex ancient communities in Northern México and the American Southwest. It was an impressive center of commerce, religion, and political power. Mike Whalen and Paul Minnis (2003:315) consider Paquimé to be one of the largest, and most complex, ancient communities north of Mesoamerica. Paquimé was a powerful trade center locally, but was also connected to a wider trade network. Paquimé traders likely interacted with Aztatlán cities along the Pacific coast, communities in the jungles of the Yucatán, and desert villages in the American Southwest. Items from these trade partners include millions of marine shell pieces from the western coast, copper items from the mountains along the western coast, and pottery from sites in the American Southwest. Evidence of parrots likely imported from the Yucatán were discovered in the form of breeding pens and hundreds of sacrificial macaw and turkey burials located throughout the city. Sometime around the beginning of the fifteenth century (c.a. 1450 A.D.), however, Paquimé began to unravel, and the site was eventually abandoned.

Di Peso excavated a large portion of Paquimé during the late 1950s and early 1960s. During his time at Paquimé Di Peso acquired aerial imagery of the entire site from multiple angles and altitudes. The aerial images he captured are extremely useful for viewing the city layout and its relationship to the surrounding terrain, water sources, and other natural resources. Di Peso's images provide a valuable historic view of Paquimé during Di Peso's excavations.

Following Di Peso's tradition of recognizing the value of aerial imagery to better visualize the enormity of Paquimé, archaeologists from BYU conducted aerial reconnaissance of Paquimé in the summer of 2015 using the fixed wing X100 UAS. Similar to the Ad Deir flight, eight GCPs were placed across the landscape and recorded using a Trimble GeoXH GPS. Positions for each GCP were processed using Trimble's Pathfinder Office with the majority of the GCPs recorded at between 30–50 cm in accuracy.

The take-off and landing locations were about 700 meters northwest of the center of Paquimé. Flight planning was performed using Gatewing's Quickfield software, and in-flight monitoring was maintained using Micropilot's Horizon 3.4, which runs on a Trimble Tablet PC. The X100 flight over Paquimé covered 0.54 km2 (133 acres or 53 hectares) in about 32 minutes, and flew 150 meters above the ground. The flight plan had a forward and sideways overlap of 80 percent. Weather conditions, as well as wind speed and direction were monitored using a Kestrel 4500 weather meter. During the flight the camera captured 422 3648 x 2736 pixel photographs. Each photo was taken with a 6.0 mm focal length, 1/250 shutter speed, f/4.0, and an ISO of 100. These photographs provided the raw data needed to produce a series of new maps, models, and visualizations using Pix4D's Pix4Dmapper software. This data was later post-processed using Agisoft Photoscan.

Pix4Dmapper used to calculate a 5.67 average ground sampling distance (GSD) based on the 150 meter flight altitude and camera settings. The quality check after initial processing returned a median of 24,761 key points per image, with all images enabled. The relative difference between initial camera parameters and optimized parameters was 0.07% which is well under the recommended 5% variation. Pix4Dmapper calculated 14,608.6 matches per calibrated image and determined a mean RMS error of 0.094 m for the eight ground control points. In addition, 2D links between matching images were strong over the majority of the target area. Based on the high accuracy and overlap, Pix4Dmapper was able to successfully compute corrected camera positions and generate automatic tie points between the photographs. This produced accurate, georeferenced maps and models in a variety of formats. Results include a georectified orthomosaic of the entire city of Paquimé, a DSM used for slope surface analysis, and a georeferenced plan map of Paquimé with a 50 cm contour interval. In addition, Pix4Dmapper was used to create 3D visualization animations from numerous angles and vantage points.

Documenting Paquimé using a small UAV to collect aerial images, combined with the numerous tools provided by Pix4Dmapper, offered the ability to efficiently and accurately map this ancient city at a high level of detail. Analysis of these aerial images provides new insights that traditional methods might not achieve without an exorbitant amount of

Figure 6. One of the 422 aerial photographs captured by the X100 to create an orthomosaic of Paquimé.

time and funding. In addition, total station or GPS mapping methods would be problematic at Paquimé, because portions of the city cannot be accessed due to their fragility.

Based on the point cloud generated using Pix4Dmapper, an orthomosaic was compiled from all 422 separate photographs (Figure 6). The point cloud also provided the ability to calculate and measure noted features in three dimensions. For example, measurements of various buildings and architecture were possible using the polyline, surface, and volume tools in Pix4Dmapper. For example, based on measurements from the Pix4Dmapper volume tool, "Reservoir 2" could hold approximately 828 m3 (828,000 liters/218,734 gallons) of water when completely full (Figure 7). In this case, these tools are helping evaluate the number of people that may have lived in Paquimé based on what is understood about human water consumption in hot and arid environments, compared to the capacity of Paquimé's reservoirs.

From the same point cloud 50 cm contour lines in shapefile format were generated to provide elevation data for a topographic map drafted from the orthomosaic. A DSM was also exported to ESRI's ArcMap for slope analysis and hillshade modeling. In addition, a polygonal mesh was constructed from the point cloud for creating 3D models and animations. A topographic map was drafted in Adobe Illustrator using Avenza's MAPublisher plugin.

The orthomosaic and the DSM slope model provided the background to digitize all of the archaeological features mapped by Di Peso. The 50 cm contour shapefile was imported into the Adobe Illustrator map using the same Avenza plugin, thus maintaining georeferencing for all digitized elements. This is likely the first comprehensive topographic map of Paquimé that includes all of the architectural

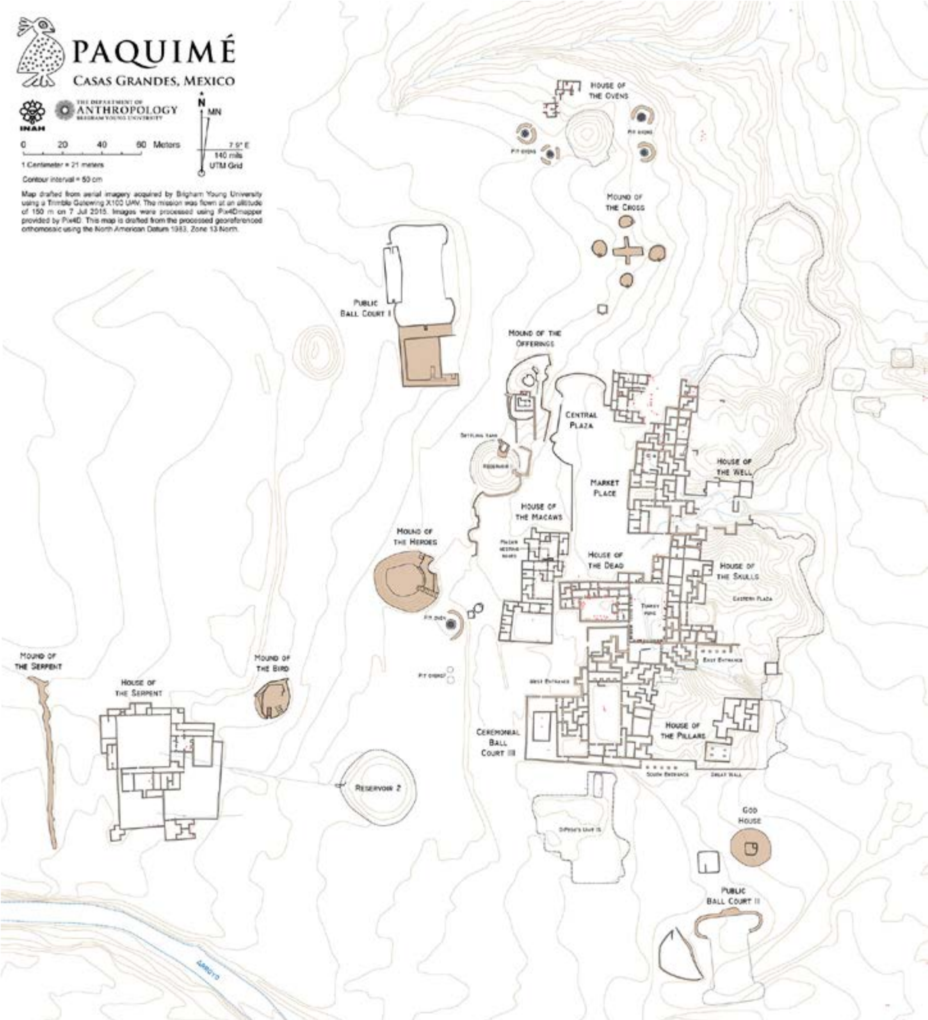

Figure 7. Map drafted in Adobe Illustrator using the Avenza MAPublisher plug-in. Contours were generated from a digital elevation model produced from the orthomosaic created in Pix4Dmapper. Architectural features were drawn directly from the orthomosaic.

features noted by Di Peso in a georeferenced format. This is an important resource that provides precise spatial information for future conservation and exploration efforts.

The DSM generated in Pix4Dmapper was also imported into ESRI's ArcMap for slope analysis and hillshade models to visualize the variation in terrain and architecture across Paquimé (Figure 8). The slope analysis results show steeper angles with warmer colors and flat surfaces in cool colors. The large pit ovens located near the "House of Ovens", on the north end of Paquimé, are especially visible due to their steep sides which display as red rings.

Interestingly, two round circles visible in the orthomosaic, located between the "Mound of the Heroes" and "Reservoir 2", were thought to be additional pit ovens; however, they barely appear in the slope analysis with only a 2.8–7.70 slope.

The results from the slope analysis also helped identify several areas that are likely unexcavated portions of Paquimé. Mounds to the east of the "House of the Skulls" and northeast of the "House of the Well" are quite visible in the slope analysis results and in the hillshade model. In addition, further east are two areas that look like they may be structural, based on their shape, size, and proximity to Paquimé proper. Moving south, to just below the "Ceremonial Ball Court II", Di Peso's "Unit 15" is very visible in the slope analysis model, and is another probable unexcavated area of Paquimé. Linear features, including aqueducts, and possible terrain alterations can be seen as well. It is unclear whether some of the linear elements are modern or ancient, but this data will help find these features during additional field work.

A hillshade model which uses a gray-tone shaded relief to enhance variation in surface terrain was also helpful for visualizing the site. This is similar to the color gradient used in the slope analysis, but it represents a smoother surface. Similar to the slope analysis image, the same unexcavated areas, structures,

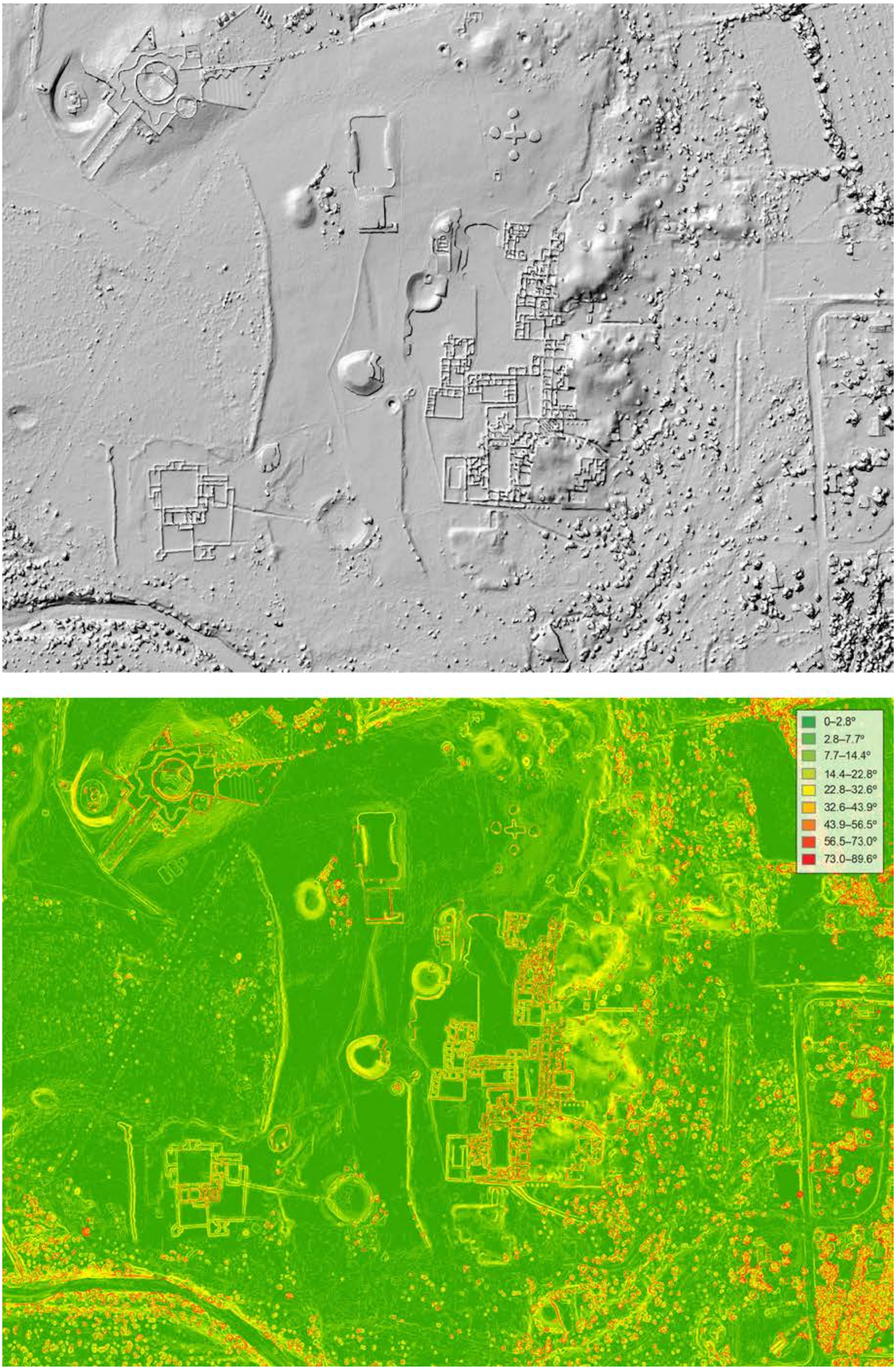

Figure 8. Images of the digital surface model (above) and the slope analysis results (below).

Figure 9. Map of west México showing the location of the Santo Domingo site near the modern city of Puerto Vallarta, Jalisco.

and linear features are quite visible. Both hillshade and slope analysis models have proven useful for identifying these subtle changes in the terrain that are not evident in the orthomosaic alone. This short exercise shows the importance of using multiple methods to examine aerial images of archaeological sites. The ability to import the DSM into ESRI's ArcMap helped identify important architectural features at Paquimé that may not have been visible otherwise. Consequently, this new information will help with future exploration or protection of the remaining uncovered portions of the city.

Santo Domingo Site, Jalisco, México

The Santo Domingo site is an unexcavated Aztatlán site located on the Pacific coastal plain of West México (Figure 9). It is located in the hills above the modern town of Ixtapa and roughly 8 kilometers northeast of Puerto Vallarta. Susan Evans and David Webster (2001:58) explain that West Mexican Aztatán sites date from A.D. 900 to A.D. 1450 and spread from along the Pacific coast from "central Jalisco up to the Sinaloa/Sonora border, and extended up into the western fringe of the Mexican plateau from the Jalisco/Michoacan border area in the south to central Durango in the north." Michael Mathiowetz (2017:1), Daniel Pierce (2017:218), and Charles Kelley (2000) note that trade was an integral part of Aztatán culture in West México, and there is good evidence they were trading cacao, finished copper ornaments, marine shell, pottery, cloth, and obsidian to areas far outside their homeland.

In the Spring of 2017 a team of BYU archaeologists joined Dr. Michael Mathiowetz from Riverside City College and INAH archaeologist Mauricio Garduno Ambriz as part of an initial effort to document several important Aztatlán sites located in the coastal heartland in Nayarit and Jalisco, México. A total of five sites were flown using a DJI Phantom 4 Pro UAS. The goal was to collect photogrammetric imagery of each site to produce georeferenced orthomosaics, topographic maps, and digital elevations models. Three of these sites (Las Animas, San Juan de Abajo, and Ixtlán Del Rio) are considered Aztatlán political centers (Mathiowetz 2017:2).

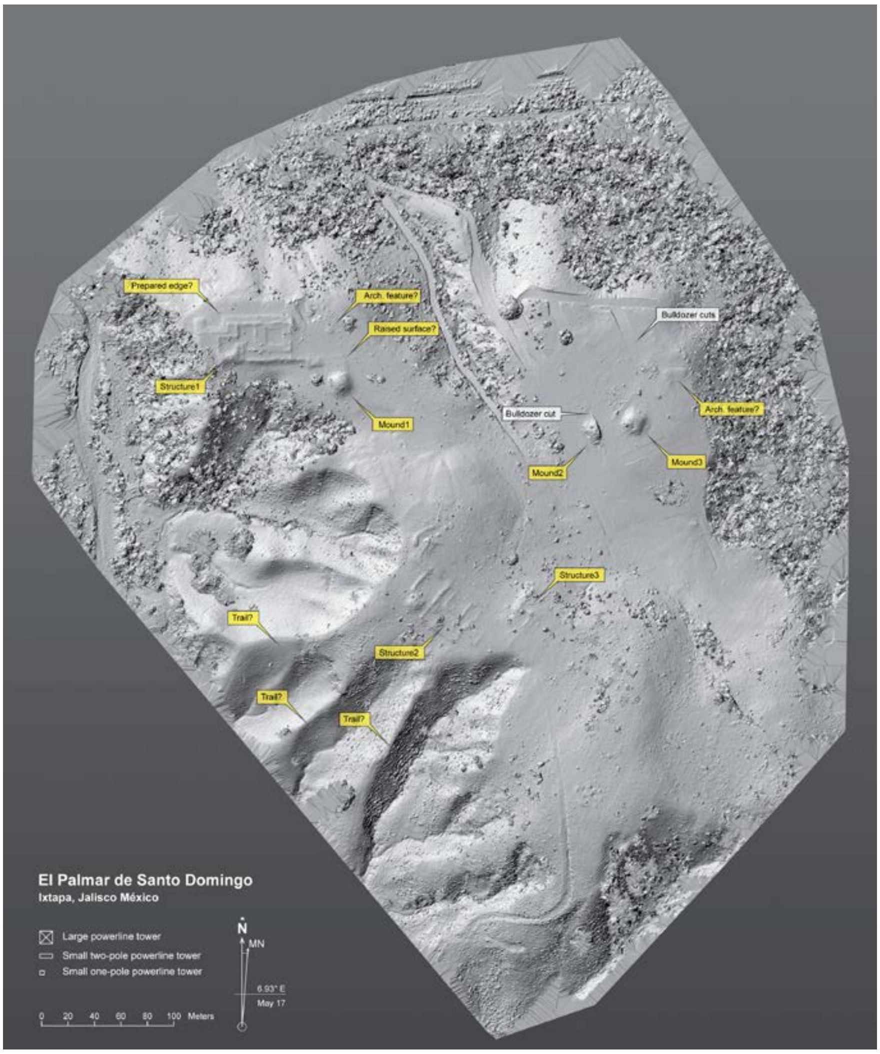

Figure 10. Annotated map of the Santo Domingo site with a DSM generated from Agisoft Photoscan as the base layer. Note the visible bulldozer tracks and damaged mound in the northeast portion of the site which were not visible in the orthomosaic.

These flights started the "first long-term, extensive regional survey and excavation program in the Aztatlán coastal heartland" (Mathiowetz 2017:2). The goal for incorporating UAVs in this project was to provide detailed maps as part of the larger documentation effort needed to conserve and excavate these critical, but generally understudied Aztatlán sites. The flights at the Las Animas, San Juan de Abajo, and Ixtlan Del Rio sites were all successful in achieving our goals; however, we were asked to fly and additional site named Santo Domingo that is currently under immediate threat from residential development.

The site was flown using a DJI Phantom 4 Pro (P4P). This UAV is a small, multi-rotor UAV is capable of flying for about 30 minutes at varying altitudes and a range of 3 to 7 kilometers. Flying at these distances is not recommended, however, as many regulations require continual line-of-sight with any UAV. The P4P has various "smart" capabilities including obstacle avoidance using infrared sensors and vision systems. The onboard camera is mounted to a gimbal and has a 1 inch CMOS sensor capable of 20 megapixels. The P4P was flown at the sites in México using DJI's Ground Station Pro app. This app allows users to easily define a flight plan, overlap percentage, flight time, camera settings, and others useful settings. Once calculated, the flight plan is uploaded to the UAV and then automatically flown with minimal user intervention unless required. Take-offs and landings are typically automatic, and can be performed in small areas, unlike fixed-wing UAVs which require larger clearings. For the Santo Domingo flight, the P4P flew at an altitude of 100 meters to clear large power lines and towers cutting through the site. The UAV covered an area of about 0.25 km2 (67 acres or 27 hectares) in approximately 15 minutes. During the flight, the onboard, gimbal-mounted camera recorded 156 5472 x 3078 pixel georeferenced images. These images were captured using the DJI FC6310 camera with a 9 mm lens. The camera was set to f/6.3 with a shutter speed of 1/640 and ISO 100. Each photo was automatically geotagged for georeferencing purposes.

Images captured from the Santo Domingo site were processed using Agisoft's Photoscan Pro in order to produce a variety of outputs using SfM processing. All 156 photos were accurately calibrated and aligned resulting in 138,352 unique tie points between the images and a ground sampling distance of 3.39 cm/pixel. A dense point cloud consisting of 22,575,078 points was generated from the camera alignments. A polygonal mesh consisting of 1,505,003 total triangular faces and 756,518 vertices was then generated from the dense point cloud. Based on the dense point cloud, an orthomosaic and DSM were created to examine the site for the location and association of architectural features not easily visible on the ground. In addition, a tiled texture model was produced to examine the model texture in high resolution. This is one of Photoscan Pro's more powerful tools, because "it allows for responsive visualisation of large area 3D models in high resolution" (Agisoft Photoscan 2018:19).

Previous pedestrian surveys and maps by Joseph Mountjoy (2003) documented several mounds and possible wall alignments at the site. Recently, local archaeologist noted where construction work was underway to develop the area for housing. In one area a large mound had been cut through with heavy equipment. Initial examinations of the orthomosaic did not reveal any identifiable traces of architectural elements or alignments, but the DSM offered a much more useful view. The DSM was imported into ESRI's ArcMap which was used to generate a hillshade that revealed several well defined architectural features (Figure 10). These features include three multi-room, walled structures, three mounds, two unidentified architectural features, and two prepared platform areas. Recent bulldozer cuts are visible throughout the eastern part of the site, along with where Mound 2 was cut through. In addition, several ridge lines appear to be flattened and may be prehistoric trails used to access the Santo Domingo site. Further examination is required to test this hypothesis. Based on these results, a hillshade created from a DSM, which was based on a dense, high resolution point cloud created using SfM, proved extremely valuable for identifying these features.

These datasets were used to map these Aztatlán architectural features quickly and accurately, as well as note the presence of modern bulldozer activity damaging features at the Santo Domingo site.

Conclusions

This paper described a few examples of how aerial photogrammetry and structure-from- motion modeling can be used to accurately map large-scale sites, identify obscured archaeological features, and measure three-dimensional space. Harnessing the data within these images offers the potential to uncover additional, and often unseen patterns and information about the archaeological sites we study. This was true for all three case studies. Results from the Ad Deir flight provided extremely useful information to plan and execute a controlled and organized survey of a particularly rugged and complex area. In addition, the SfM data were integral in creating a high-resolution topographic map of the Ad Deir plateau. Models generated from the SfM also provided useful animations of this dynamic terrain to help viewers visualize the archaeological complexity of the plateau, as well as see the interconnected nature of the site itself. At Paquimé, data generated from aerial imagery captured via a UAV also provided the framework for a topographic map of the site, as well as a host of other valuable analysis to identify unexcavated portions of the city. The integration of geospatial analysis with SfM models also proved to be a powerful combination of tools to analyze reservoir capacities at Paquimé. This information could lead to additional studies about the available water resources and the population size these reservoirs could have sustained. Finally, the flight over the Aztatlán site of Santo Domingo in West México resulted in an SfM model also analyzed with geospatial tools to identify architectural features not easily visible on the ground or in aerial imagery. In addition, the SfM model was able to show bulldozer activity and damage to the site surface and at least one prehistoric mound.

Unmanned Aerial Systems are capable of providing stunning aerial imagery, and with advances in SfM and geospatial analysis, we have access to tools that can vastly improve our remote sensing capabilities. The cost and time to learn how to use these instruments and software is less expensive and quicker than ever before. Additional advancements and the miniaturization of various radar, LiDAR, and multi-spectral sensors will offer future tools to document, analyze, and discover archaeological sites at high levels of detail. The future of UAS use in archaeological research will only continue to grow as he related technologies continue to develop.

References

Agisoft Photoscan 2018 Building tiled model. In: *Agisoft PhotoScan User Manual Professional Edition, Version 1.2,* 14 March 2018. Available at http://www.agisoft.com/pdf/photoscan-pro_1_2_en.pdf.

Center for Advanced Spatial Technologies 2018 *Digital Photogrammetry in Geospatial Modeling and Visualization,* 13 March 2018. Available at http://gmv.cast.uark.edu/ photogrammetry/.

Center for Photogrammetric Training 2008 *History of Photogrammetry*, 13 March 2018. Available at https://spatial.curtin.edu.au/local/docs/HistoryOfPhotogrammetry.pdf.

Di Peso, C C 1974 Casas Grandes: The Medio Period, Vol. 2. In: Fenner, G (ed.) *Casas Grandes: A Fallen Trading Center of the Gran Chichimeca*. Flagstaff, AZ: The Amerind Foundation, Inc. Dragoon Northland Press.

Evans, S T and Webster, D L 2001 *Archaeology of Ancient Mexico and Central America: An Encyclopedia*. New York and London: Garland Publishing, Inc.

Kelley, C 2000 The Aztatlan Mercantile System: Mobile Traders and the Northwestern Expansion of Mesoamerican Civilization. In: Foster M and Gorenstein S (eds) *Greater Mesoamerica: The Archaeology of West and Northwest Mexico.* Salt Lake City, UT: University of Utah Press.

Mathiowetz, M 2017 *Connecting the U.S. Southwest/ Northern Mexico to West Mexico through Collaboration: UAV Remote Sensing and Mapping at Aztatlán Civic Ceremonial Centers*. Research proposal submitted to the Arizona Archaeological and Historical Society, University of Arizona, Tucson, Arizona.

Micheletti, N Chandler, J H and Lane, S N 2015 Structure from Motion (SfM) Photogrammetry. In: *Geomorphological Techniques, Ch. 2, section 2.2.* British Society for Geomorphology.

Mountjoy, J B 2003 *Arqueología del Municipio de Puerto Vallarta*, 10 August 2018. Available at https://archaeology.uncg.edu/Vallarta/index.html.

Pierce, D E 2017 Finding Class in the Glass: Obsidian Source as a Costly Signal. *Journal of Anthropological Archaeology* 48:217–232. DOI: https://doi.org/10.1016/j.jaa.2017.05.001

Schenk, A 2005 *Introduction to Photogrammetry.* Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University.

Westoby, M J Brasington, J Glasser, N F Hambrey, M J and Reynolds J M 2012 Structure-from-Motion photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications. *Geomorphology* 179:300–314. DOI: https://doi.org/10.1016/j.geomorph.2012.08.021

Whalen, M E and Minnis P E 2003 The Local and the Distant in the Origin of Casas Grandes, Chihuahua, Mexico. *American Antiquity* 68(2):314–332. DOI: 10.2307/3557082

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Robert J. Bischoff & James R. Allison
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Using Nonoptimal or Archival Photographs for Constructing 3D Models

Robert J. Bischoff
School of Human Evolution and Social Change,
Arizona State University
rbischoff@asu.edu

James R. Allison
Department of Anthropology,
Brigham Young University
jallison@byu.edu

Abstract

Photogrammetry is well on its way to becoming a standard part of archaeology. As helpful as new technology can be, it is not always applicable to past excavations. We recommend following best practices for all current work, but photographs from prior excavations are generally not ideal for photogrammetry. We demonstrate the utility of photogrammetry under various, problematic conditions using test cases from three archaeological sites excavated between the 1930s and the current decade. We discuss some of the successes, challenges, and conditions where we succeeded or failed to create a viable 3D model. Our results indicate that successful and accurate 3D models can be created from excavation photographs taken under a variety of circumstances and without accompanying camera metadata. The major limiting factor we found was lack of overlapping coverage of the subject, which proved problematic to a greater or lesser degree in all of our case studies.

Keywords: Photogrammetry, archival images, 3D models

Introduction

Structure from motion (SfM) is a branch of photogrammetry used to create 3D structure from 2D photographs. In common usage, the term “photogrammetry” usually refers to SfM, and we follow this convention. Photogrammetry is well on its way to becoming a standard part of archaeology. As helpful as new technology can be, it is not always applicable to past excavations. We recommend following best practices for all current work, but photographs from prior excavations are generally not ideal for photogrammetry. Our purpose in this paper is to explore what can be done with photogrammetry under problematic conditions using photographs taken from several years to decades in the past. This has been called historical, archival, or retrospective photogrammetry (Wallace 2017).

A major challenge for this type of photogrammetry is assessing the accuracy of the 3D model. The best method is to compare the photogrammetry model to a model collected via a laser scanner (e.g., Skarlatos & Kiparissi 2012). Accuracy can also be compared to measurements taken directly from an artifact or feature. To determine accuracy, we compared a 3D model obtained via a laser scanner with a photogrammetry model generated from non-optimal photographs. In this paper, we discuss some of the successes, challenges, and conditions where we succeeded or failed to create a viable 3D model. Our results indicate that successful and accurate 3D models can be created from excavation photographs taken under a variety of circumstances and without accompanying camera metadata. The major limiting factor we found was lack of overlapping coverage of the subject, which proved problematic to a greater or lesser degree in all of our case studies.

Most of the models in this study were created with Agisoft PhotoScan Standard (2018; version 1.4.1), which is widely used, inexpensive, and relatively user friendly. Thus, creating 3D models from archival or nonoptimal photographs can be done with little expense or training. Prior studies in various fields have used historical photographs with satisfactory results. Several studies have used archived aerial imagery for generating photogrammetric 3D models (e.g., Bakker & Lane 2017; Mölg & Bolch 2017; Papworth et al. 2016; Peterson, Klein & Steward 2015; Sevara et al. 2018), and others have successfully used archival photographs for terrestrial photogrammetry (e.g., Bitelli et al. 2017; Falkingham, Bates & Farlow 2014; Grun, Remondino & Zhang 2004; Ioannides et al. 2013; Lallensack et al. 2015; Maiwald et al. 2017; Snavely, Seitz & Szeliski 2008; Wallace 2017). These projects, along with our test cases discussed here, demonstrate the feasibility of creating 3D models using photographs not intended for, or optimal for, use in photogrammetry.

We have modelled four structures at three sites in the U.S. Southwest, all in the state of Utah (see Figure 1). We first discuss the methods used to create the 3D models and some common challenges. We then discuss the results for each 3D model we created by site. We end by summarizing our findings and recommendations.

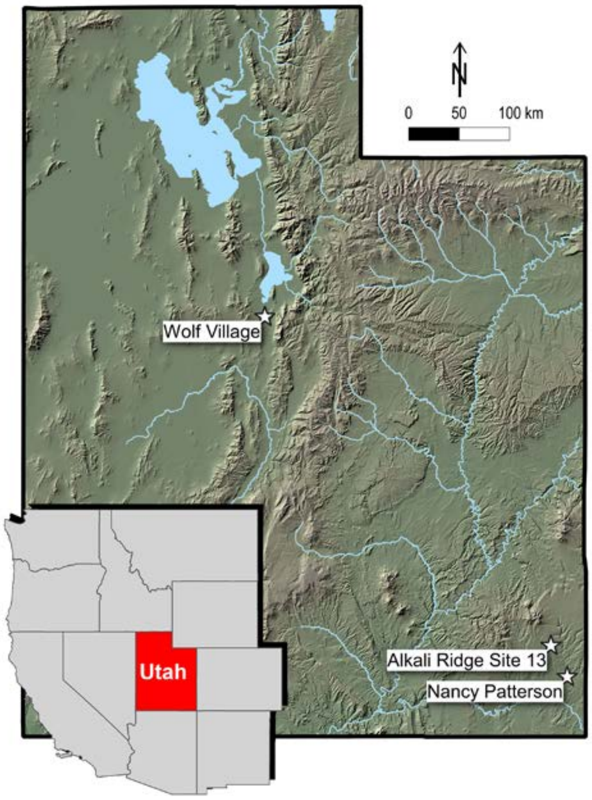

Figure 1. Map showing locations of sites used in the case studies.

Methods

As previously mentioned, Agisoft Photoscan was used to create the 3D models from the selected photographs. While some details are specific only to Photoscan, the general principles are likely applicable to other software, although Wallace (2017: 614) notes that Photoscan has features often better suited for what he calls "retrospective photogrammetry" than some other software. While we attempted to create one model using the professional version, all the successful models were created using the standard version. The cost is significantly lower, which reduces the price barrier for photogrammetry. The primary benefit, in this case, for using the professional version is the ability to manually place tie points or markers on photographs to assist the software in tying photographs together (see Wallace 2017). While this can be helpful in many situations, it is encouraging that we were able to achieve satisfactory results without the added hassle of manually adding tie points. Eliminating this step speeds the process, although overall this can be a time consuming endeavor. This article is not a photogrammetry tutorial and is not intended to instruct a beginner, rather, we highlight the additional steps we took and challenges we encountered to achieve results using problematic photographs. While we explain some options specific to Photoscan, we will not discuss each option in detail. Our intent is to encourage others to attempt photogrammetry in similar situations and to share some methods we found helpful.

Photograph Selection

The first step in photogrammetry is to acquire an image set. Generally, more photographs are better than fewer, but with some qualifications. Some difficulty is experienced when photographs were taken at different scales (i.e., close ups with long-distance overviews), but also when there are duplicate or near duplicate photographs and insufficient overlap for other photographs (see Wallace 2017: 611). In the latter case the software may only align the duplicate photographs and ignore other photographs. These issues can be solved by removing the problematic photographs. Our examples do not deal with photographs taken under different lighting and other con-

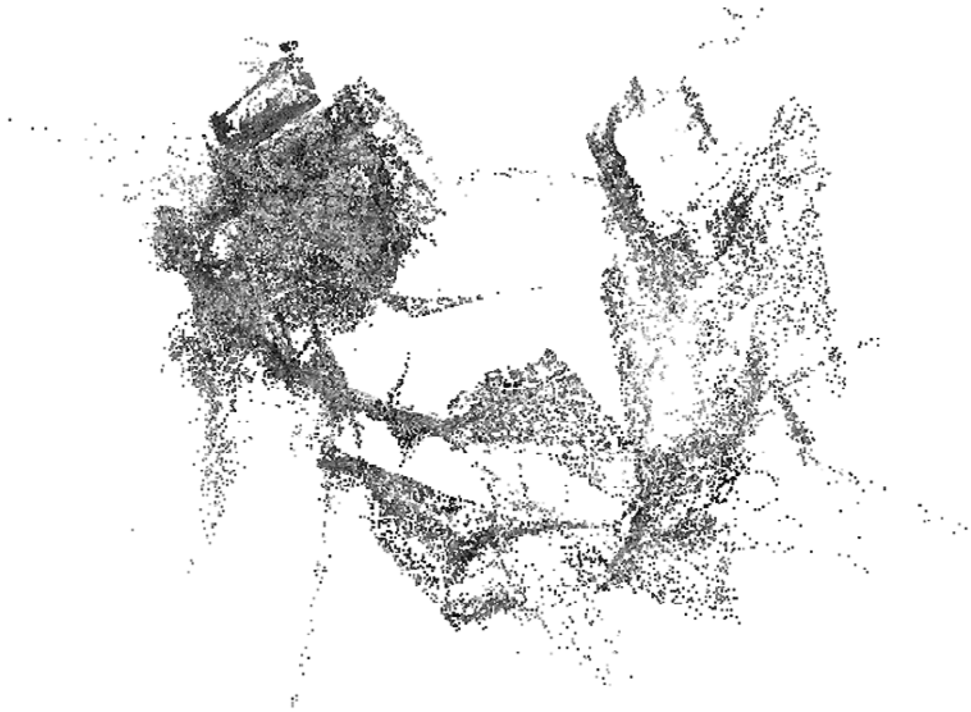

Figure 2. Demonstration of an initial, failed camera alignment in Agisoft Photoscan.

ditions, but using photographs taken with the same lighting, etc., is recommended. We did not have major issues using photographs that had people and objects inconsistently placed. These undesired inclusions can be masked, but we found success by merely ignoring them.

Camera Alignment

The greatest challenge we found is aligning cameras. Once accomplished, generating the 3D model is usually unproblematic, as long as a sufficient number of photographs were aligned. Camera alignment is usually automatic for good photographs, but difficulties occur when the photographs were not captured with appropriate equipment or settings. The primary cause of failed camera alignment is often insufficient coverage. Multiple camera angles are necessary for 3D construction, and the software frequently has difficulty aligning photographs taken at widely different scales. Unfortunately, this situation usually cannot be improved in the circumstances we consider here, as the opportunity to collect more photographs is generally not an option using archival photographs.
If overlap is sufficient for a 3D model, which is often only determined after trial and error, then usually some photographs will align correctly, while others (sometimes most) of the photographs will either not be aligned or will be misaligned. The critical advice at this point in the process is to not become discouraged and to continue working with the photographs to create a proper alignment. The first step is to attempt alignment using multiple alignment configurations. What follows is a mostly nontechnical exploration of the various options related to camera alignment in Photoscan software, and which settings we recommend based on our experience and trials.

Photoscan has several available options, and the highest possible settings are not always best. The primary setting for camera alignment is called "Accuracy." We generally start with high, which uses the photographs at their original scale. The highest setting upscales the photograph by 4, while the medium setting downscales the photograph by a factor of 4. We do not recommend settings below medium. We find that high usually works best, but in some situations the highest or medium settings have provided better results. "Pair preselection" can speed up the alignment process. Typically, we do not select this option, but occasionally we have found better results with this option selected. We usually leave the key point tie limit at the default value, as we have found little difference when changing this value. We often obtain best results with the "Tie point limit" set to zero, which, in this case, means there is no limit to how many points are used to tie photographs togeth-

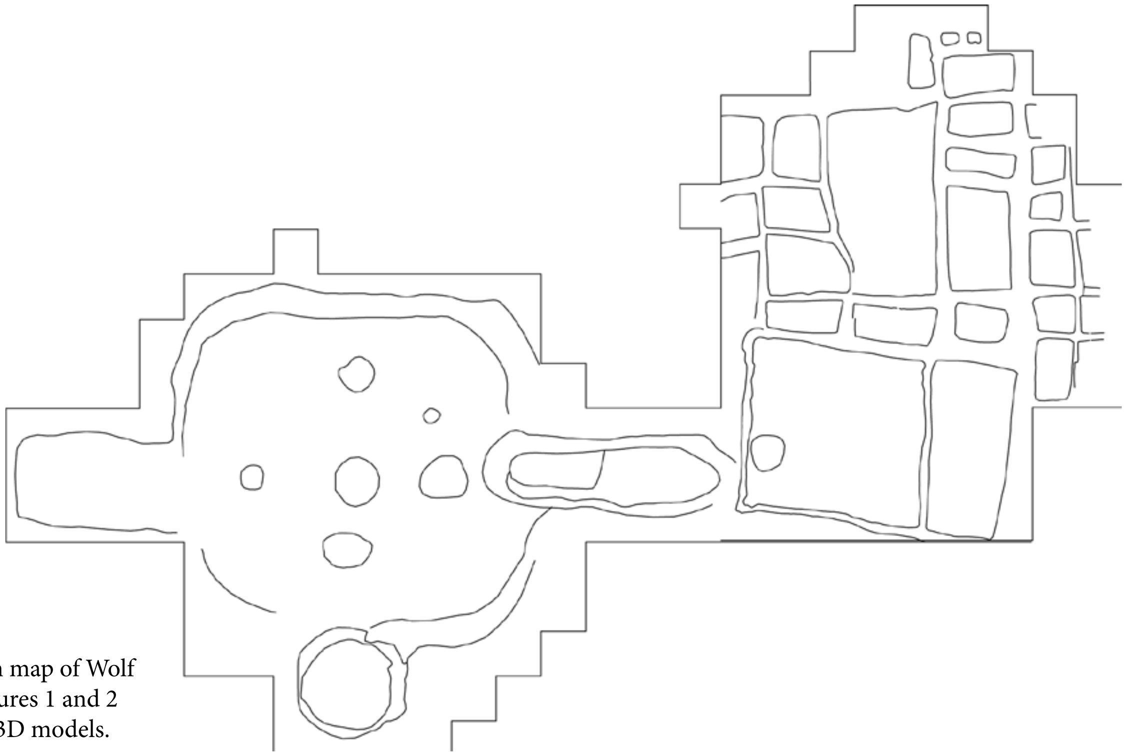

Figure 3. Plan map of Wolf Village Structures 1 and 2 used to align 3D models.

er. Using infinite tie points increases the processing time but not significantly so. Masks can be applied to remove people, objects, or scenery that are not meant to become part of the 3D model, however, we were often able to obtain good results without masking any parts of the photographs, even with people and objects variously placed within the photographs. Masking can become quite time consuming and it is easier to avoid this step when possible. The last option for camera alignment is "Adaptive camera model fitting," which concerns the automatic selection of camera parameters. We recommend leaving this unchecked to start, but selecting this option can sometimes improve results. The best advice we can give for these settings is to patiently experiment with your dataset and determine which settings result in the best possible camera alignment.

Often, some photographs cannot be aligned, and in the case of Figure 2 many photographs are clearly misaligned. We have found great success manually resetting camera alignments. Photoscan has several useful features to aid in this endeavor. Points that are clearly out of alignment can be selected to determine which photographs are causing the problem and can be reset and realigned. A common problem is the misalignment of axes. For example, several models we created resulted in the expected horizontal axis, but some of the photographs were misaligned resulting in one or more axes lying on different planes (see Wallace 2017: 613–614). Our recommendation is to reset all poorly aligned cameras until all aligned cameras are correctly positioned and the remaining geometry accurately represents the subject. Once accomplished, the problem photographs may be realigned manually one at a time or a few at a time. If the realigned camera causes too much noise, or stubbornly refuses to align properly, then it is best to remove it. One option to further correct this issue is to use manual tie points in the professional edition of Photoscan. But we were able to obtain good camera alignments for each model without resorting to this more time-consuming method. Figure 2 demonstrates the initial camera alignment for a structure discussed later. These alignment results are not promising; however, accurate geometry was captured after attempting multiple alignment configurations and manually aligning photographs. The remainder of the process typically follows standard photogrammetry procedure and does not need to be discussed here.

Scale, Rotation, and Alignment

Often, 3D models must be manually scaled to allow measurement of the model. If models must be combined, as is done in two of the case studies, then the models must not only be scaled appropriately to each

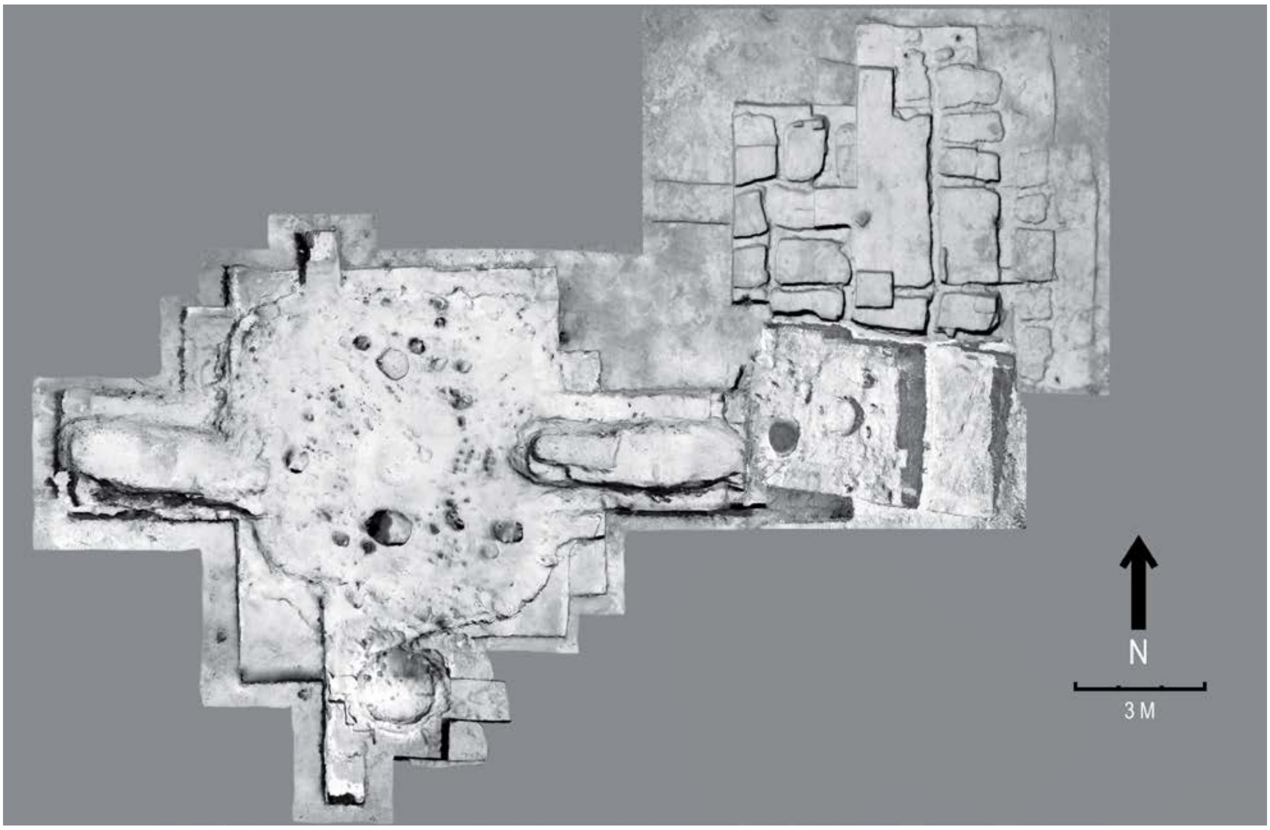

Figure 4. Render of aligned 3D models for Wolf Village Structures 1 and 2. This model uses photographs from 2012 for the main part of the structure on the left and photographs from 2013 for the antechamber at the south end of the structure. Photographs of the main two rooms of the structure on the right were taken in 2010, while the photographs for the cluster of small rooms to the north were taken via an unmanned aerial vehicle in 2016.

other, but must also be aligned, rotated, and positioned appropriately. The open source software Blender (2018; version 2.78) was used for these purposes. Blender offers a full suite of 3D modelling tools but has a relatively high learning curve. A full description of the processes used to scale and orient the models is beyond the scope of this paper; however, a few notes on scaling and alignment are germane. The 3D models created in Photoscan lack a true scale. An object or portion of the 3D model may have a known length, such as a scale reconstructed in the model, and this can be used to scale the entire model. Plan maps can also be used where available. We found using plan maps was the most effective method for our situation. The basic process is to add the plan map to Blender as a background photo, scale the photograph using the scale included in the plan map, and then scale the object itself to align with the plan map. This also worked well for aligning multiple models. Figure 3 shows the plan map for both Structures 1 and 2 at Wolf Village (see case study below), which are adjacent. Figure 4 is composed of four 3D models that were aligned using the combined plan map for the structures. Blender was also used to render 2D images of the 3D models. Photographs can be rendered with perspective or as orthophotos, which is particularly useful for archaeological applications. Automatic alignment can also be used. The open source software CloudCompare (2016; version 2.7) and Meshlab (Cignoni et al. 2008, Meshlab 2016; version 2016) both have automatic alignment options, but these options require more identical features in the 3D models than we had in our models. Determining the accuracy of the 3D models is a principal concern. The Wolf Village case study will demonstrate the accuracy of one of the photogrammetry 3D models compared to a 3D model created via laser scanner.

Accuracy Comparison

Perhaps the best method to determine the accuracy of these models is to compare the model to a model of known accuracy. In the case of Structure 2 at Wolf Village, we are fortunate to have laser scan data

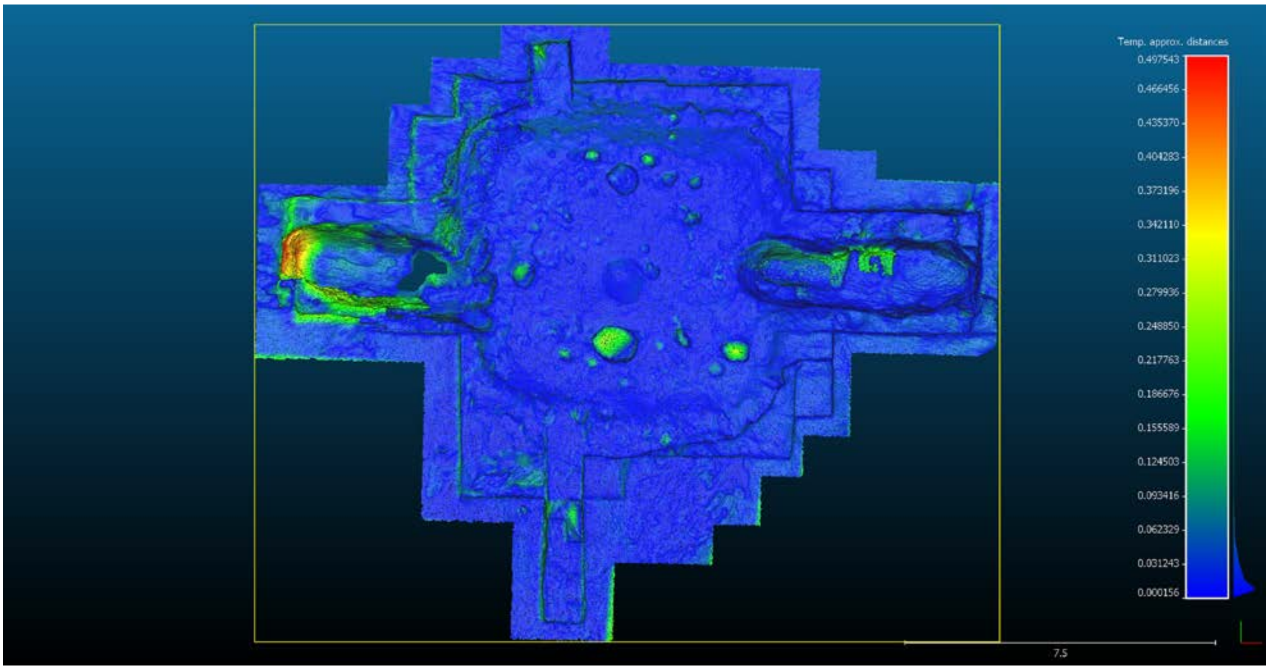

Figure 5. Cloud to cloud comparison between the laser scan and the photogrammetry 3D models of Wolf Village Structure 2.

captured by Brigham Young University staff archaeologist Scott Ure at approximately the same time as the photographs used for photogrammetry. The laser scanner is a FARO Focus 3D 120 with ±2 mm accuracy. CloudCompare was used to compare the models. The mesh models were converted to point clouds and aligned and registered. The cloud to cloud comparison was used to determine the distance between the two point clouds. The result, Figure 5, shows the aligned point clouds and their differences. The western tunnel of this structure has the greatest variation, while many of the subsurface features are not well matched. Figure 6 shows a comparison for the west tunnel between the photogrammetry version, the laser version, and an excavation photograph used in the photogrammetry that was taken at approximately the same time as the laser scan. From these views, the photogrammetry model may best represent the physical structure of the tunnel. Overall, we found the accuracy of the photogrammetry to be at least comparable to the laser scan model.

Case Studies

We have modelled four structures at three sites in the U.S. Southwest, all in the state of Utah. The sites are Wolf Village, Alkali Ridge Site 13, and Nancy Patterson Village. All photographs from Wolf Village and all the photographs for the successful 3D model from Alkali Ridge Site 13 were taken using digital cameras with accompanying metadata. The photographs used in the failed reconstruction from Alkali Ridge Site 13 and the Nancy Patterson site were taken with film cameras and were scanned from negatives or from prints. While the use of scanned photographs vs digital provides different challenges for 3D modelling, several challenges were common for all of the models.

Wolf Village

The first site we created 3D models from is Wolf Village, a Native American farming village in the northern part of the state of Utah that dates primarily to the AD 1000s and early 1100s (Johansson, Richards & Allison 2014). The 3D modelling focused on two unusually large structures at the site, Structures 1 and 2. Structure 1 was a multi-room earthen surface structure. Two relatively well-constructed rooms were excavated during the 2009 and 2010 field seasons. In 2013 and 2016, approximately 20 more small rooms were excavated, attached to the north side of the first two excavated. These small rooms were apparently later additions to the structure, as the walls were built on fill that rested against the north wall of

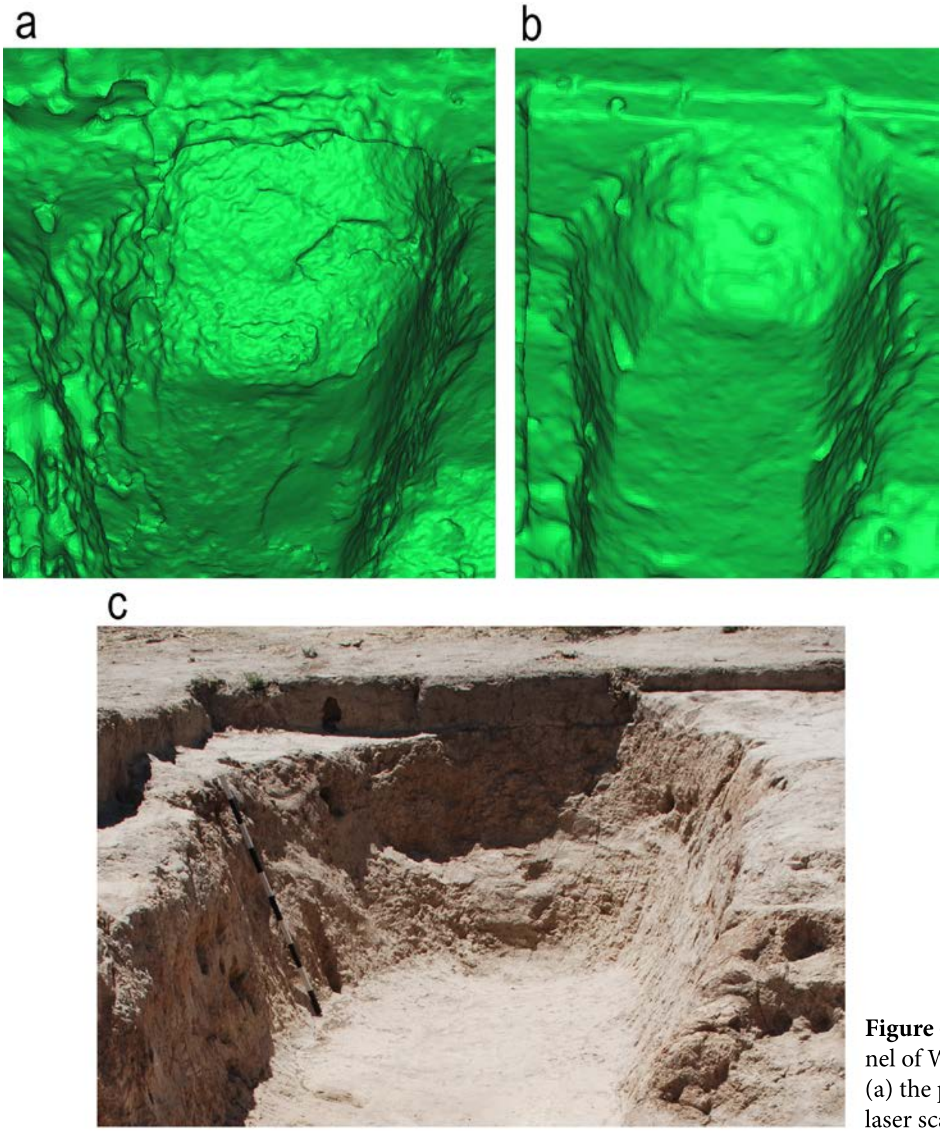

Figure 6. Comparison of the west tunnel of Wolf Village Structure 2 between (a) the photogrammetry model, (b) the laser scan, and (c) an excavation photo.

the first two rooms excavated. In addition to being smaller, the walls of these rooms were thin and poorly built, and floors were difficult to discern. These smaller rooms may have been used for storage, but there is little evidence that they were used at all, and one interpretation is that they were added simply to increase the size and impressiveness of the building.

Just west of the surface structure was Structure 2, a large pit structure totaling 80 square meters, including two large deep tunnels that appear to be entrances as well as a small antechamber on its southern edge. The structure was found at the end of the 2010 field season, then most of it was excavated in 2011 and 2012, although the southern antechamber was not excavated until 2013.

Because the excavation of these two structures was spread over six different field seasons, neither structure was ever completely uncovered at once, nor were major parts of the two adjacent structures open at the same time. Our original intent was to create a 3D model of Structure 2 that included the antechamber excavated the year following the excavation of the main part of the structure and to show this structure's close association with Structure 1. All structures were backfilled for preservation purposes at the end of each season, and it was impractical to remove the backfill each year. The creation of 3D models allowed us to combine models created from photographs taken in different years to show all completed excavations from these structures in one model.

The challenges we faced in creating these models were that these photographs were not intended for photogrammetry and were taken with a telephoto

Figure 7. Render of aligned 3D models from Alkali Ridge Site 13. This model uses photographs taken in 2012 of the three rooms at the upper right and photographs taken in 2013 of the room at the upper left and the partially excavated rooms in the lower part of the photographs.

lens with different zoom levels, which is strongly not recommended for photogrammetry. Some photographs also have people and various objects inconsistently moving between shots. Also, there are some areas with too few photographs to construct a completed 3D model. A few photographs were unusable, but we were able to create 3D models of all the desired features. This was done without masking any of the moving objects, which saved time. We combined models of Structure 2 from the 2012 excavation, the antechamber from 2013, Structure 1 as excavated in 2010, a pit in this structure that had to be modelled separately, and the remainder of Structure 1 as excavated in 2016. Of these models, only Structure 1 from 2016 was made from photographs intended for photogrammetry (these photographs were captured via an unmanned aerial vehicle).

The alignment of the models was accomplished using the plan map of the combined structures to align the photographs within Blender. One benefit of aligning the models this way is that we realized that the antechamber had been placed in the incorrect position on the map by almost a meter. This demonstrates an immediate benefit of these 3D models, in that they can eliminate some human error and are usually more accurate than hand-drawn maps. Figure 4 shows an orthographic render taken directly above the structures. The 3D models have several small holes where sufficient overlap was lacking. For aesthetic purposes, these holes can be repaired using 3D modelling software, or, if 2D renders are the concern, image editor software may be used to clean the holes, rough edges, or other problems, as was done in Figure 4. As discussed in the methods section, the accuracy of this model is comparable to a high-resolution laser scan. Photographs from the next site were taken using the same camera and the accuracy appears to be similar except for thin, stone slabs that were

Figure 8. Render of color 3D model of Nancy Patterson kiva. All photographs were taken in the same year.

problematic for photogrammetry using the available photographs.

Alkali Ridge Site 13

Alkali Ridge Site 13 is an Ancestral Pueblo village in southeastern Utah that dates to the late AD 700s. As one of the earliest aggregated villages in the Four Corners area (so-called because it is near where the corners of the states of Utah, Colorado, New Mexico and Arizona meet), it is an important site in the archaeology of the U.S. Southwest. A large portion of the site was excavated in the 1930s (Brew 1946); recent work at the site in 2012 and 2013 included re-excavating several of the rooms that had been excavated 80 years earlier, then expanding those excavations into adjacent unexcavated rooms. The impetus for creating 3D models of the excavated surface rooms at this site are similar to the reasons listed for the Wolf Village case study. Three rooms were excavated and photographed in 2012. One additional complete room and portions of two others were excavated in 2013, but the 2013 excavations were not immediately adjacent and closing photographs did not overlap between these areas. We created four 3D models from excavations over these two years and combined them into one model. Compared to Wolf Village, there were fewer usable photographs, and there were a greater number of objects and people in the photographs, but the greatest difficulty was the presence of relatively thin stone slabs lining the walls of the rooms. These difficulties led to several distortions in addition to the holes in the model; however, the general physical shape of the rooms turned out well and should be comparable in accuracy to the 3D models created for Wolf Village. These models were aligned by using comparable features in each model, which were later compared with an aligned plan map to verify accuracy. We found the accuracy sufficient for our purposes and, aligned together, these models allow us to render the equivalent of an aerial orthophoto (see Figure 7).

We also attempted reconstruction of some of the same rooms from photographs taken during the original excavations in the 1930s. While we were able to generate some 3D data, overall, we were unable to generate anything useful, even after attempting to add numerous manual tie markers in

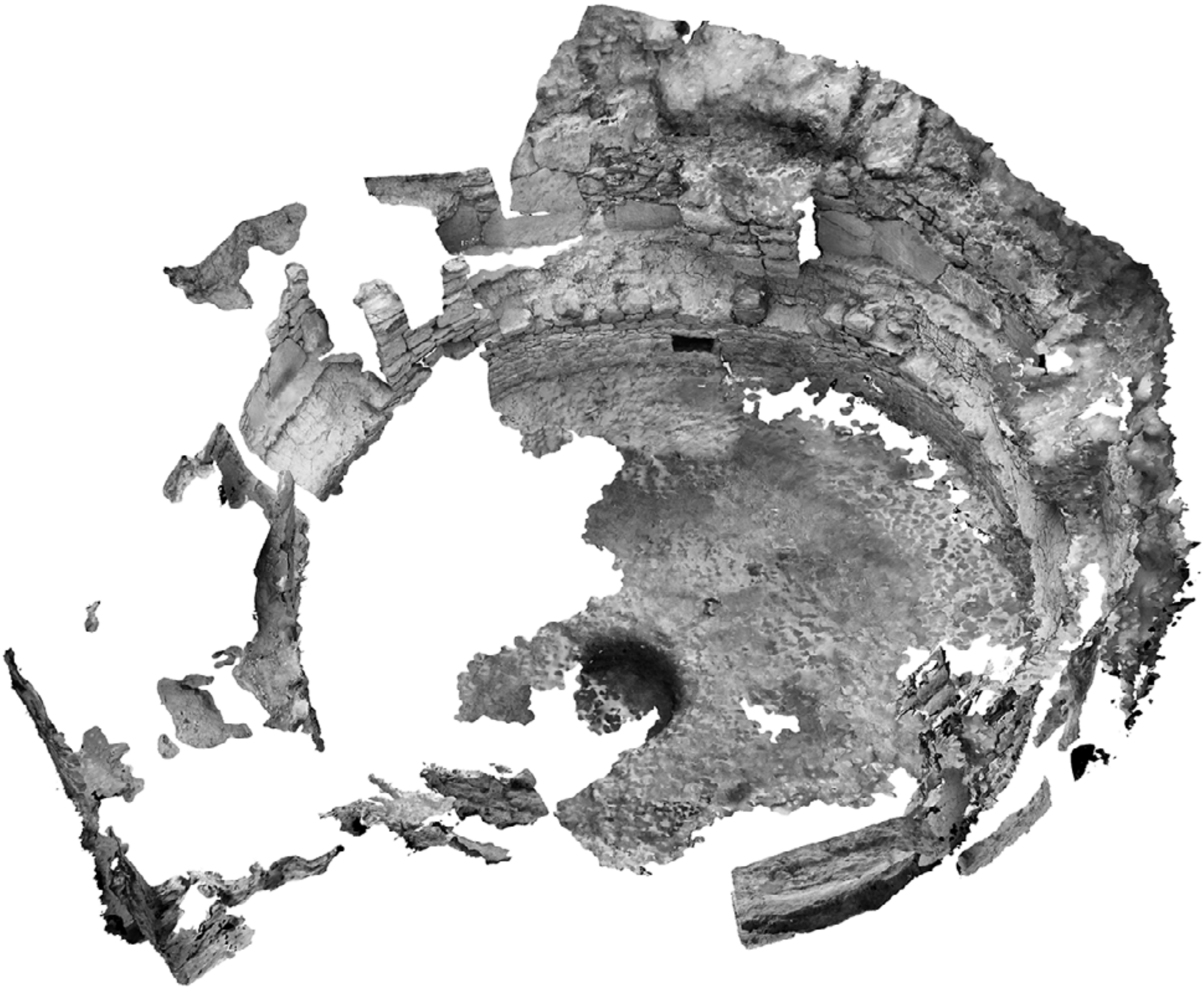

Figure 9. Render of black and white 3D model of Nancy Patterson kiva. All photographs were taken in the same year.

an attempt to force the software to recognize associations between photographs. While the alignment of some photographs was encouraging, we found that we lacked sufficient coverage to create a viable 3D model.

Nancy Patterson Village

Our last study was a reconstruction of a kiva from the Nancy Patterson Village site, another Ancestral Pueblo site in southeastern Utah (Thompson et al. 1986, 1988). The site was used for hundreds of years, beginning in the AD 600s, but it was a large village at two different time periods: close to 900 and again in the 1200s. The kiva we attempt to model dates to the 1200s occupation. It was trenched in 1984, then most of it excavated in 1985. Unfortunately, the depth of the structure, extraordinarily hard fill, the complexity of digging through and documenting the burned roof fall, and limited manpower meant that the field season ended before the floor could be completely cleared. The kiva was partially backfilled but was still damaged by water pooling in the structure over the winter. By the start of the 1986 field season, some masonry had slumped off the wall. The excavation was finished in 1986, but we were left with photographs from 1985 that showed most of the kiva with masonry intact, but the floor not completely exposed, and photographs from 1986 that showed the floor but with damaged masonry. We therefore hoped to be able to combine photographs from the two seasons to create a model that combined photographs from the two field seasons to show the structure as it would have appeared if fully excavated and undamaged.

Photographs on the project were all taken with paired 35mm SLR cameras, one with color film, the other with black-and-white, with the goal of producing approximately duplicated photographs with each film type. Slides were digitized using a high-resolution scanner. No metadata exists for these photographs. Our goal was to use both the black and white and color photos; thus, we converted the color photographs into grayscale. Each camera was aligned separately as best as possible and then the camera calibration was saved. When both cameras were calibrated the photographs were added together and the separate calibrations were assigned to each photo. Unfortunately, we were unable to align any cameras without significant distortion; however, we were able to create 3D models out of the photographs from the separate cameras using photographs from 1986. The color model, as shown in Figure 8, has many holes, but the modelled geometry appears accurate. The black and white 3D model (see Figure 9) provided more coverage, but the geometry is clearly more distorted, particularly the floor of the structure. It also took many more attempts to align the cameras than for the color model. The biggest problem with this structure is that most photographs were taken close up of separate features, and the overview photographs did not capture all sides of most parts of the kiva. We found that we lacked sufficient photographs to accomplish our purpose of merging the models to create an intact model prior to the damage between excavation seasons.

Discussion and Conclusion

The goal of this study was to experiment with photogrammetry using photographs not explicitly meant for 3D modelling. These photographs came from both recent excavations and photographs held in archives for decades. These photographs cannot be considered optimal for photogrammetry based on technical reasons, such as a variable zoom lens, missing information, such as camera metadata, and particularly for the lack of sufficient overlap between photographs. Our purpose for these models was primarily visual, and, in some cases, we were able to obtain high quality overviews of architectural features, including the equivalent of aerial orthophotos. We found the ability to combine models made during different excavations seasons to be particularly useful. Using photogrammetry, we were able to take standard excavation photos and create models showing features in contexts that did not exist during excavation. Other than lack of adequate overlap, which is difficult to rectify (although see Wallace 2017), camera alignment is the principal difficulty. This step, typically automatic, often requires time-consuming manual adjustments and experimentation with settings. Additionally, our comparison between a 3D model created from nonoptimal photographs and a precise laser scan demonstrates that these 3D models can attain accuracy comparable to a high-accuracy laser scanner.

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References

Agisoft Photoscan Standard, computer software 2018. Available from: <http://www.agisoft.com/>. [last accessed 28 August 2018].

Bakker, M and Lane, S N 2017 Archival photogrammetric analysis of river-floodplain systems using Structure from Motion (SfM) methods. *Earth Surface Processes and Landforms*, 42(8): 1274–1286. DOI: https://doi.org/10.1002/esp.4085

Bitelli, G, Dellapasqua, M, Girelli, V, Sbaraglia, S and Tinia, M 2017 Historical photogrammetry and terrestrial laser scanning for the 3d virtual reconstruction of destroyed structures: a case study in Italy. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-5/W1: 113–119. DOI: https://doi.org/10.5194/isprs-archives-XLII-5-W1-113-2017

Blender, computer software 2018. Available from: <https://www.blender.org/>. [last accessed 28 August 2018].

Brew, J O 1946 *Archaeology of Alkali Ridge, Southeastern Utah: With a Review of the Prehistory of the Mesa Verde Division of the San Juan and Some Observations* *on Archaeological Systematics.* Cambridge, Massachusetts: Peabody Museum.

Cignoni, P, Callieri, M, Corsini, M, Dellepiane, M, Ganovelli, F and Ranzuglia, G 2008 MeshLab: an open-source mesh processing tool. In: Scarano, V., Chiara, R.D., and Erra, U. (eds.) *Eurographics Italian Chapter Conference.* The Eurographics Association. DOI: https://doi.org/10.2312/LocalChapterEvents/ItalChap/ItalianChapConf2008/129-136.

CloudCompare, computer software 2016. Available from: <https://www.danielgm.net/cc/>. [last accessed 28 August 2018].

Falkingham, P L, Bates, K T and Farlow, J O 2014 Historical photogrammetry: Bird's Paluxy River dinosaur chase sequence digitally reconstructed as it was prior to excavation 70 years ago. *PLOS ONE*, 9(4): e93247. DOI: https://doi.org/10.1371/journal.pone.0093247.

Grun, A, Remondino, F and Zhang, L 2004 Photogrammetric Reconstruction of the Great Buddha of Bamiyan, Afghanistan. *The Photogrammetric Record*, 19(107): 177–199. DOI: 10.1111/j.0031-868X.2004.00278.x

Ioannides, M, Hadjiprocopis, A, Doulamis, N, Doulamis, A, Protopapadakis, E, Makantasis, K, Santos, P, Fellner, D, Stork, A, Balet, O, Julien, M, Weinlinger, G, Johnson, P S, Klein, M and Fritsch, D 2013 Online 4d reconstruction using multi-images available under open access. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5/W1: 169–174.

Johansson, L D, Richards, K K and Allison, J R 2014 Wolf Village (42UT273): A Case Study in Fremont Architectural Variability. *Utah Archaeology*, 27(1): 33–56.

Lallensack, J N, Sander, M, Knötschke, N and Wings, O 2015 Dinosaur tracks from the Langenberg Quarry (Late Jurassic, Germany) reconstructed with historical photogrammetry: Evidence for large theropods soon after insular dwarfism. *Palaeontologia Electronica*. DOI: https://doi.org/10.26879/529

Maiwald, F, Vietze, T, Schneider, D, Henze, F, Münster, S and Niebling, F 2017 Photogrammetric analysis of historical image repositories for virtual reconstruction in the field of digital humanities. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3: 447–452. DOI: https://doi.org/10.5194/isprs-archives-XLII-2-W3-447-2017

Meshlab, computer software 2016. Available from: <http://www.meshlab.net/>. [last accessed 28 August 2018].

Mölg, N and Bolch, T 2017 Structure-from-Motion Using Historical Aerial Images to Analyse Changes in Glacier Surface Elevation. *Remote Sensing*, 9(10): 1021. DOI: https://doi.org/10.3390/rs9101021

Papworth, H, Ford, A, Welham, K and Thackray, D 2016 Assessing 3D metric data of digital surface models for extracting archaeological data from archive stereo-aerial photographs. *Journal of Archaeological Science*, 72: 85–104. DOI: https://doi.org/10.1016/j.jas.2016.05.005

Peterson, E B, Klein, M and Steward, R L 2015 *Whitepaper on structure from motion (sfm) photogrammetry: constructing three dimensional models from photography*. Denver: Bureau of Reclamation.

Sevara, C, Verhoeven, G, Doneus, M and Draganits, E 2018 Surfaces from the visual past: recovering high-resolution terrain data from historic aerial imagery for multitemporal landscape analysis. *Journal of Archaeological Method and Theory*, 25(2): 611–642. DOI: https://doi.org/10.1007/s10816-017-9348-9

Skarlatos, D and Kiparissi, S 2012 Comparison of laser scanning, photogrammetry and sfm-mvs pipeline applied in structures and artificial surfaces. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, I-3: 299–304. DOI: https://doi.org/10.5194/isprsannals-i-3-299-2012

Snavely, N, Seitz, S M and Szeliski, R 2008 Modeling the world from internet photo collections. *International Journal of Computer Vision*, 80(2): 189–210. DOI: https://doi.org/10.1007/s11263-007-0107-3

Thompson, C, Baker, S A, Allison, J R, and Wintch, K L 1986 *The Nancy Patterson Village Archaeological Research Project: Field Year 1985 - Preliminary Report No. 3*. Brigham Young University Museum of Peoples and Cultures Technical Series No. 86-27, Provo.

Thompson, C, Allison, J R, Baker, S A, Janetski, J C, Loosle, B, and Wilde, J D 1988 *The Nancy Patterson Village Archaeological Research Project: Field Year 1986 - Preliminary Report No. 4*. Brigham Young University Museum of Peoples and Cultures Technical Series No. 87-24, Provo, Utah.

Wallace, C A B 2017 Retrospective photogrammetry in Greek archaeology. *Studies in Digital Heritage*, 1(2): 607–626. DOI: https://doi.org/10.14434/sdh.v1i2.23251

Valentina Vassallo, Giacomo Landeschi & Sorin Hermon
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Digging in Excavation Diaries: Digital Re-Assessment of Stratigraphy in 3D GIS. The Sanctuary of Ayia Irini, Cyprus

Valentina Vassallo
Science and Technology for Archaeology Research Center, The Cyprus Institute
v.vassallo@cyi.ac.cy

Giacomo Landeschi
Lund University
giacomo.landeschi@ark.lu.se

Sorin Hermon
Science and Technology for Archaeology Research Center, The Cyprus Institute
s.hermon@cyi.ac.cy

Abstract

During the last years, numerous research projects focussed on re-examination of past excavations, giving birth to re-evaluation of their documentation and material or to new discoveries. The aim of this paper is to present an ongoing research on the digital re-assessment of the Ayia Irini sanctuary's stratigraphy using 3D GIS, by corroborating published material with data extracted from the original excavation diaries. The project wants to digitally reconstruct the site in order to question the positioning of finds and their setting within the sanctuary, the existence of natural versus human-made features and the possible impact of flooding episodes as proposed by the archaeologists who excavated the site.

Keywords: Ayia Irini sanctuary, terracotta figurines, excavation diaries, stratigraphy re-assessment, 3D GIS

Introduction

Recently, several research projects were devoted to re-examination of past excavations, allowing the re-evaluation of their documentation and material or bringing forth new discoveries. Such boost was given both by the need of digitizing legacy data and by the possibility of re-evaluating such data with digital technologies (De Felice & Fratta 2016; Haggis & Antonaccio 2015).

The combined use of 3D modelling and mixed 2.5/3D analysis, archaeometric investigations, as well as archive data, old drawings, maps and photos, shed new light onto past excavations and new elements were identified. For example, features that were not recorded and published because they were not understood, or elements not visible due to limitations or absence of the past technologies have been acknowledged and used for new interpretations. In some cases, especially in excavations of the 20th century, when the stratigraphic method started to be used in archaeology, some inconsistencies were spotted (Landeschi et al. 2018; Houby-Nielsen 2016). Moreover, the instruments used to document were manual and therefore accuracy (e.g. measures, exact positions) was affected by human errors.

Any excavation, as continuously repeated by archaeologists, is a destructive process (Lucas 2001: 35)[1], therefore it would be impossible to re-produce the original situation in reality. Digital technologies give us the possibility to re-construct past excavations and re-analyse the context, their buildings and artefacts, virtually. The possibility to apply new techniques previously not available help us to possi-

1 An excavation can be also considered a sort of archive that brings along the archaeologist approach and interpretation, as well as his/her biases, and it transforms the record from an objective into a subjective one (Roosvelt et al. 2015).

Figure 1. Map of the sites excavated by the SCE during its activity in Cyprus (see Karageorghis et al. 1977: 6). The Ayia Irini sanctuary is in north Cyprus, currently occupied by Turkish troops (the red line shows the border).

bly simulate all steps occurred during the excavation and to visualize things not seen before. Moreover, digital technologies allow us to take into account large volumes of data at the same time, facilitating a holistic visualization.

Context and Research Aims

The new possibilities given by technologies in GIS and 3D, enabled the flourishing of various projects aimed at solving different kind of problems in the field of archaeology and cultural heritage. 3D GIS systems have been employed for better managing archaeological data and solving issues regarding how to store, retrieve, and eventually analyse them. More specifically, the chance to develop work pipelines that allow the archaeologists to import in GIS conspicuous amounts of 3D data characterized by complex and texturized geometries considerably changed the research approach both in the field and in the lab (Landeschi et al. 2015).

During the last years, the use of 3D GIS supported and enhanced several research lines, bringing new light to the archaeological discussion. At the base of such research projects there is of course the necessity of documentation aimed at the analysis of sites and artefacts, as we have already mentioned as being the boost of the digital technologies use in humanities, with different specific scopes. Poggi (2016) for example, in his contribution presents a documentation workflow aimed at the analysis of ongoing archaeological excavations through the use of an image-based 3D modelling technique. Monitoring, preservation and restoration aims are the main topic of further research: Landeschi et al. (2016a) discuss about the possibility of assessing damage of archaeological sites through the combination of image-based 3D modelling techniques and GIS, while Campanaro et al. (2016) propose 3D GIS as processing knowledge tool for cultural heritage monitoring, restoration and therefore preservation. Finally, the analytical and interpretative part, always present in all the aforementioned projects, are deepen by Piccoli (2016), who suggests an enhancement of GIS with 3D procedural modelling approach for ancient urban interpretation, by Landeschi et al. (2016b) and Richards-Rissetto (2017) both proposing 3D GIS as a platform for visual analysis in different case studies, and by Dell'Unto et al. (2017) who put forward the use of 3D GIS as simulation platforms for supporting field interpretation.

The study presented here fits in this research frame and its major scope is the 3D documentation and re-evaluation of past excavations and their material in order to obtain new information useful to their analysis and interpretation. Particularly, the current paper presents a digital re-assessment of the Ayia Irini (Cyprus) sanctuary's stratigraphy using 3D GIS, by corroborating published material with data extracted from the original excavation diaries. The obtained maps question the positioning of finds and their setting within the sanctuary, the existence of natural versus human made features and the possible impact of flooding episodes. Such a stratigraphic re-assessment is based on the 3D re-alignment of the artefacts found on the site, according to drawings and notes from the original excavation diaries, their

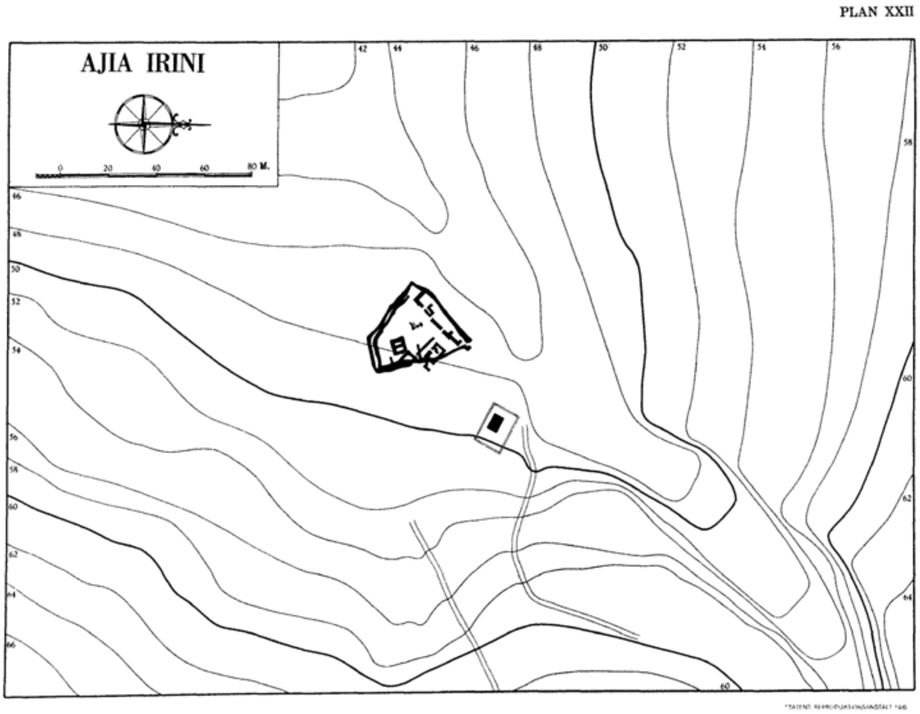

Figure 2. Plan XXII. Scale 1:80 (Gjerstad et al. 1935)

location and orientation related to the other features of the sanctuary and a re-evaluation of the nature of features described in the excavation diaries and related to them.

The Ayia Irini Sanctuary and its Finds

The Ayia Irini (Cyprus) sanctuary was excavated in 1929 by the Swedish Cyprus Expedition (SCE), and seven periods of use were identified, from the end of Late Cypriot III (ca. 1200 BC) to the Cypro-Archaic II periods (ca. 500 BC), with a small revival in the 1st century BC, and suggested that the area was flooded several times. It consists of a temenos with small buildings around an open court where, around the limestone altar and in semi-circular setting, more than 2000 terracotta statues and figurines of humans, animals, chariots, minotaurs, varying in size and shape, were found.

A peculiarity of this famous large archaeological collection is that it was divided between Sweden and Cyprus just after the excavation, and it is currently conserved in five museums. In Sweden, at the Medelhavsmuseet, together with part of the archaeological collection are also conserved the archives of the Swedish Cyprus Expedition: excavation diaries, original plans, drawings and around 10,000 photographic negatives that document the four year archaeological activities carried out by the group all over Cyprus.

The Ayia Irini sanctuary was excavated in October 1929 and in a few months was brought to light. The site is situated near the modern village of Ayia Irini, in the Morphou district in northwest Cyprus. The sanctuary is situated in an open field near the coast on rocky ground gradually sloping towards the sea. The site is in the area under Turkish military occupation since 1974 and thus inaccessible to further archaeological investigations (Figure 1). Scholars have been focussing, therefore, on reviewing published and unpublished excavated material and analysing artefacts for a better understanding of the site's stratigraphy and related chronological sequence (Houby-Nielsen 2015; Houby-Nielsen 2016; Bourogiannis & Mühlenbock 2016; Mühlenbock & Brorsson 2016).

Issues identified

Some issues have been identified after the analysis of the excavation material, of the publications and of the previous scholarships on the topic.

As previously mentioned, the Swedish Cyprus Expedition had a great importance for the Cypriot archaeology history. During the four years of activity in the island (1927-1931), the expedition conducted systematic and extensive excavations of numerous archaeological sites with the intention of establishing a chronology for the prehistory and early history of Cyprus. The SCE team consisted of Einar Gjerstad, the director of the expedition, two other archaeologists Erik Sjöqvist and Alfred Westholm and the architect John Lindros. Thanks to this group's composition, it was possible to carry out the field work at the simultaneously in different places, while Gjerstad travelled around in order to supervise and the architect Lindros to document with drawings, plans and photographs the excavations.

The first issue, already highlighted by other scholars, is the fact that the Ayia Irini's excavation was published by the SCE leader, Gjerstad, and not by the archaeologist who excavated the site, Sjöqvist. This situation could cause some inconsistencies in the interpretation of the site. The official results of the Ayia Irini excavation were published in 1935, almost six years after, and some revisions and adding to the results were published in 1948 and 1963 (Gjerstad et al. 1935; Gjerstad 1948; Gjerstad 1963). In fact, a first text regarding Ayia Irini, different from those already cited, was published in 1933 by Sjöqvist (Sjöqvist 1933). Different opinions regarding the "floods" stratigraphy emerged from the publications of Sjöqvist and Gjerstad: they respectively talk about two and four flooding events. Additionally, inconsistencies can be identified between the material published and the unpublished one: for example, the arch. Lindros' drawings present elements that are not reported in the published maps, some sections are published wrongly (e.g. in reverse), not all original maps and sections are conserved in the archives, and some layers are not identified in all parts of the site (Houby-Nielsen 2015; Houby-Nielsen 2016).

Some lack of accuracy can be detected in the maps used to identify the exact position of the sanctuary in the modern landscape. The relative reference measurement system used by the SCE is not related to any geographical coordinate system, causing difficulties in the reconstruction of the site respect to the modern landscape. Also, some inconsistencies can be identified in the maps regarding the terracottas' position. Finally, the area of Ayia Irini is not accessible for further archaeological investigations; moreover, today the archaeological remains are covered and they are not visible anymore.

Digital Re-Assessment of the Ayia Irini Stratigraphy through Published and Unpublished Material

The ongoing project presented in this paper is part of a doctoral research project: the methodology of the reconstruction and some preliminary results are reported here.

The research includes the re-positioning of 3D models of the finds' in a 3D GIS environment of the sanctuary, reconstructed through the extrusion of the 2D plans and drawings created and published by the Swedish Cyprus Expedition (Gjerstad et al. 1935), in order to have a unified access of the collection and a holistic vision of the archaeological discovery. This involves the digitization of the excavation documentation, in order to spatially contextualize the collection and to give access to data (and related metadata).

The digital re-assessment of the site's stratigraphy is performed through 3D GIS, by corroborating published material with data extracted from the original excavation diaries. The obtained maps question the positioning of finds and their setting within the sanctuary, the existence of natural versus human made features and the possible impact of flooding episodes. Such a stratigraphic re-assessment is based also on the 3D re-alignment of the finds, according to drawings from the original excavation diaries, their location and orientation related to the other features of the sanctuary and a re-evaluation of the nature of features described in the excavation diaries and related to the archaeological material.

A GIS project has been planned and built for the scope. For its creation, ESRI ArcGIS Pro 1.3 software package, has been employed. The choice of this software is due to the fact that it is able to manage 3D geometrically complex models and specific tools that at the moment are not available in other software. The first step consisted of gathering all available material useful to the construction.

A Digital Elevation Model (DEM) provided by the Department of Land and Survey, Cyprus, with a resolution of 1:25 m has been imported to be associated with an imagery of the island of Cyprus, provided by Esri, and used as a basemap to create the model of the current elevation. Successively, to better visualize the terrain, hillshade calculation has been performed. The hillshade was needed to

Figure 3. Georeference tests for finding the exact position of the sanctuary. The procedure brought to light the presence of measures' issues in the SCE plans (Vassallo©).

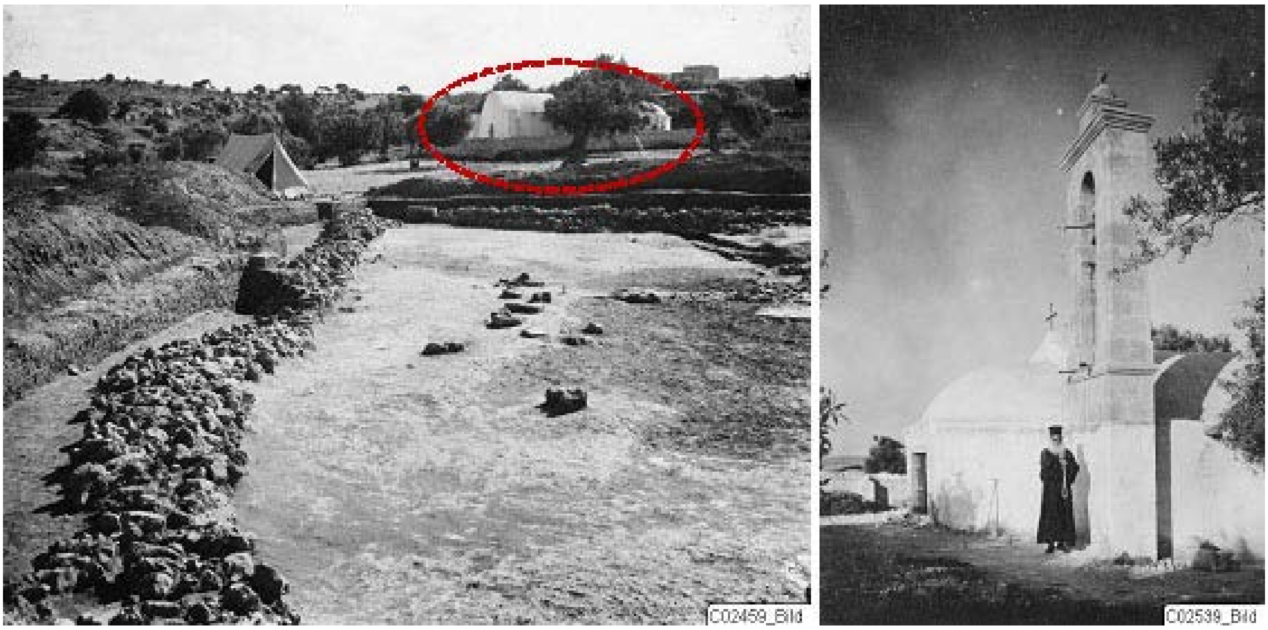

Figure 4. View from the sanctuary of the small Ayia Irini church (C02459 http://collections.smvk.se/carlotta-mhm/web/object/3924483) and Papa Prokopio on the back of the church (C02539 http://collections.smvk.se/carlotta-mhm/web/object/3926565).

emphasize the topographical discontinuities of the terrain surface, making easier to identify landscape features (possibly ground anomalies?), and to calculate how steep the terrain is. Specifically, this calculation has been made to visualize the shape of the ground and compare it with the isolines represented in the plan created by the SCE (Gjerstad et al. 1935: 643, Plan XXII; Figure 2 in this paper). Although the hillshade visualization is built on the resolution of the DEM (1:25), the slopes of the terrain became much more visible and they helped us to better position the plan during the georeferencing process.

A substantial part of the project consists, therefore, of georeferencing all architectural plans, excavation maps and images available, in order to position the sanctuary and its finds in the geographical space, and successively visualize and analyse them together.

The first question coming forward regarded the exact position of the sanctuary in relation to the modern landscape. In order to determine its position, the Plan XXII by the SCE (Gjerstad et al. 1935)

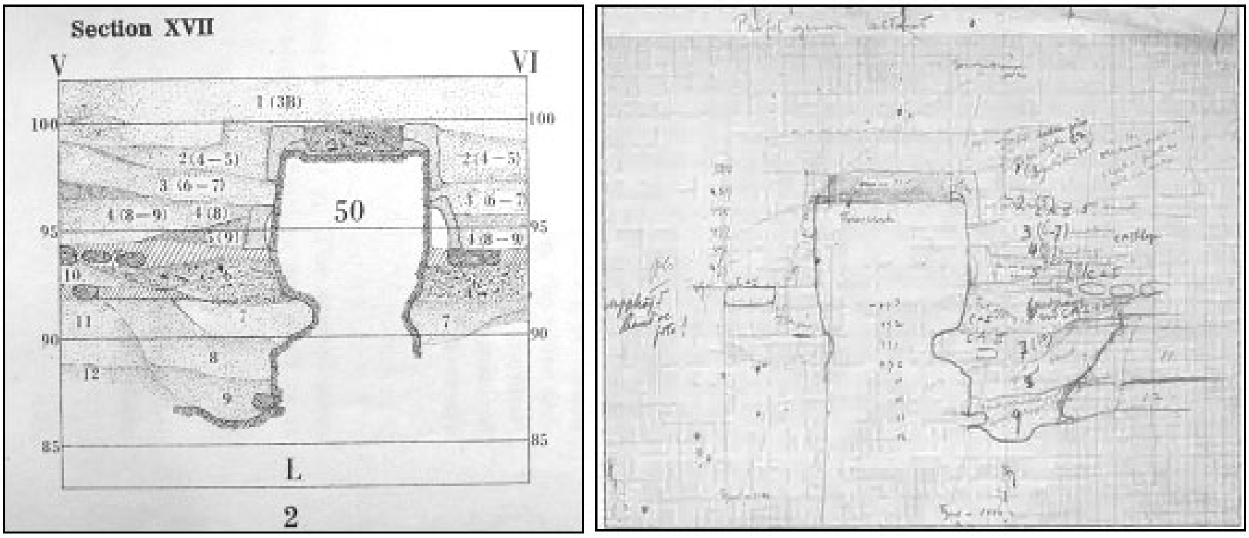

Figure 5. Wrong publication (and interpretation?) of some sections: Section XVII as published in Gjerstad et al. 1935 (left) and the same section as retrieved in the excavation diaries (13950D, http://collections.smvk.se/carlotta-mhm/web/object/3991070) (right).

(Figure 2) had to be georeferenced, since it is the only and official information regarding the location. Some issues came out from this phase of the reconstruction. The georeferencing was done trying to overlap all elements of reference drawn in the map: the slopes of the terrain, the stream bed position, the two small roads, and the church building with its enclosure. Issues concerning the scale and the elements' measurements (e.g. the church and the roads)[2] have been identified in the Plan. Unfortunately, this is something very common when it comes to old maps created with manual instruments. Some dimensions do not correspond to reality and most probably there are small errors in the position of the elements and with the scale of the plan. The errors became evident while overlapping the drawn elements of the Plan XXII on the real elements of the DEM: the process caused their distortion and consequently change of the measures.[3] To avoid that, the decision was made to georeference the plan trying to keep the measurements of the raster image stable by introducing a frame built in CAD to the map (Figure 3). This solution was employed also for the other maps to be georeferenced, in order to keep the measurements and the elements' positions stable, since it appeared that errors were going to be present in other plans and this would have brought to an increase of the error.

Old photos and photographic documentation can help archaeologists in reconstruction projects of past excavations better identify parts of the landscape (e.g. slopes and rivers), human artefacts (e.g. modern and ancient buildings) and relative distances between those elements, or in the whole reconstruction of ancient landscapes. There are many examples that demonstrate how the archaeological interpretation can be supported by archive data and can benefit from its use (Burke 2001: 224[4]): consultation of old photos and drawings for virtual reconstruction of ancient structures and their decorations (Forte 2007), use of aerial photographs and old photos for archaeological landscape reconstruction (Clark & Casana 2016).

In this vein, the old photos from the SCE archive are used to get further information regarding the location of the sanctuary and the position of the finds. For what concerns the identification of the sanctu-

2 Measuring the elements represented in the map, it appears that the church does not present real measures: the church should measure circa 14 meters, while the one drawn in the map is almost half (ca. 8 m). The measure of the church enclosure seems instead to be more precise but still not accurate.

3 An uncertainty of 2 meters from the historical plan is identified on an absolute distance of 60 meters, taken at clear identifiable points on the landscape map.

4 As underlined by Januarius and Teughels, "Peter Burke's book on the uses of images as historical evidence has brought an authoritative contribution to a theoretical and historical approach to visual material. Published in 2001, it is still very influential today. Burke evaluates different types of visual material, stressing both their strengths and their pitfalls as research subjects. Although he raises the idea that photographs bring the historian face to face with history, he also underlines the potential of visual sources as traces of the past in the present" (Januarius & Teughels 2009: 668-669).

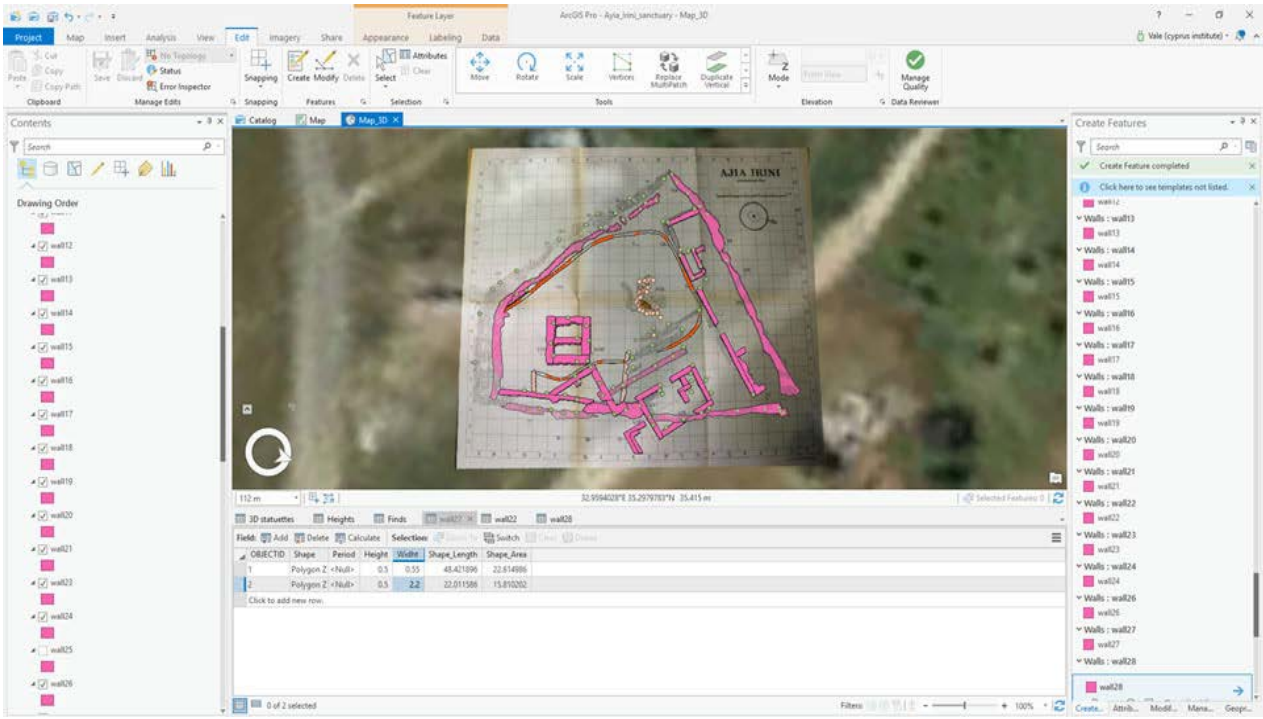

Figure 6. 2.5D reconstruction of the structures: the geodatabase contains information about the heights and widths of each wall (Vassallo©).

ary's position, we could see that some of the old pictures show the view of the small Ayia Irini church from the ancient site during the excavation; others depict Papa Prokopio, the priest who SCE cites as the first one finding a statue in his fields, next to the church (Gjerstad et al. 1935: 642)[5]. The position and direction of the church, the position of the bell tower and of the apse in respect to the ancient remains in the pictures, was compared with the Plan XXII and the DEM and it helped us locate and put in a better direction the ancient sanctuary, no longer visible today (Figure 4).

Recently, a surface recognition of the area has been performed.[6] The survey allowed us to identify the presence of some remains (most probably to be related to the sanctuary) that have been taken into consideration to better locate the site.

The successive step for the reconstruction of the Ayia Irini archaeological site consisted of the integration of the more detailed plans with sections created by the SCE, both published and unpublished. In fact, beyond the measurements issues identified in the previous step, differences between the published material and the excavation diaries data were highlighted. As Houby-Nielsen underlines in her analysis of the SCE archive, although numerous section plans were published, only some of the originals are still conserved in there. Furthermore, some inconsistencies can be detected between the excavation photos compared with the original drawings of the arch. Lindros with the published one: some sections were published in reverse[7] (Figure 5); other plans present missing parts, most probably not understood and therefore eliminated in the final publication, or changed and integrated as to better show parts that were missing or not preserved (Houby-Nielsen 2016).

Another issue regards the fact that not all the layers were identified in all parts of the site. In 1935 Gjerstad published the stratigraphy of the site with a documentation of eighteen section drawings, covering different parts of the excavated area (Gjerstad et al. 1935: 653-663). The results of the publication

5 It is interesting to highlight how the presence of the church confirms the continuity of use of the area as a religious one.

6 In spring 2018 a surface recognition of the sanctuary and of the neighbouring areas was performed by the first author for the doctoral thesis' aims.

7 Moreover, according to Houby-Nielsen none of the originals and of the published sections give sound proof of the floods' existences (Houby-Nielsen 2016).

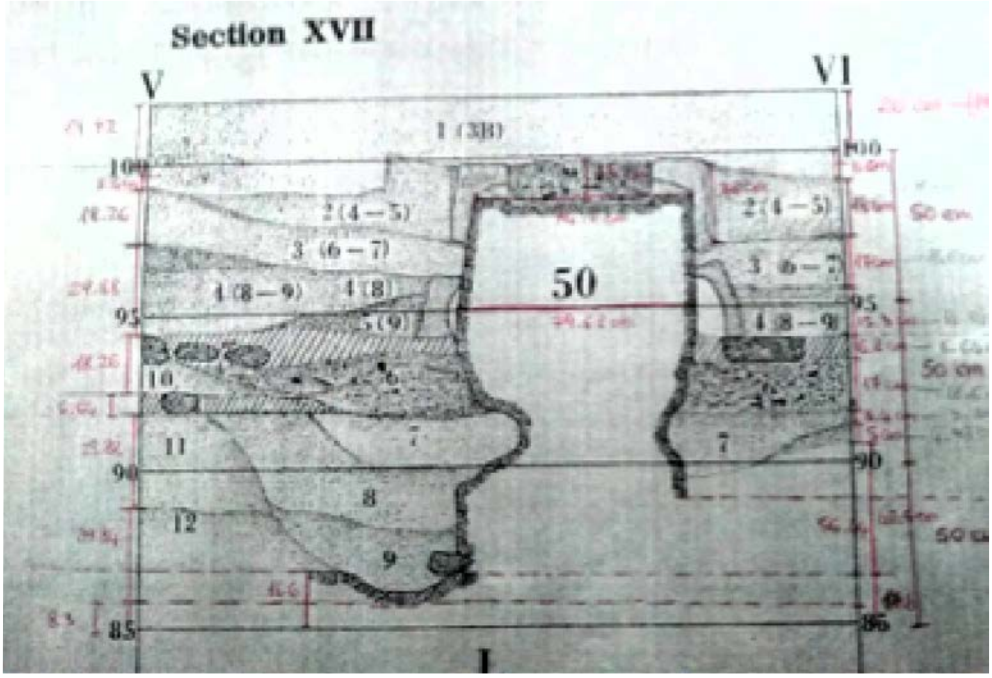

Figure 7. Calculation of the layers depth in relation to the levels published by the SCE in Section XVII (Vassallo©).

document the presence of twelve layers, which could not be identified in the whole area, associated with seven different periods on the site.[8]

All these problems in the documentation made us question if they could affect the interpretation of the stratigraphy and part of the site, and if a combined 2.5/3D visualization and analysis could contribute to the archaeological discussion. For this reason, the original section drawings, together with some redrawn maps have been integrated into the 3D environment to analyse them together with the published ones. To do so, a previous reconstruction of the architectural remains was needed. The remains are underneath the ground and not visible, therefore it was impossible to digitally document the walls directly (e.g. with laser scanner or photogrammetric technique). The only solution was to reconstruct the walls as they were at the moment of the excavation with the help of the measurements and of the heights' points provided by the SCE, respectively documented in the published material and in the arch. Lindros' original drawings.

The integration of the whole information available aims at understanding the relations between the structures, the levels and the finds. The absolute heights and thickness of the sanctuary walls have been stored in the geodatabase in order to be used to extrude polygon's features in the 3D georeferenced environment (Figure 6). Despite extrusion can be technically defined as a 2.5D operation to vertically reproject a vector polygon based on fixed z values, being the object to be extruded a wall in this case, in which typically the thickness has a constant value, the final result provided an acceptable approximation of the original volume of the standing structures observed at the time of the excavation.

This step included also the reconstruction of the structures' position compared to the modern landscape. That was the most problematic step so far, since any SCE document reported information about the datum point. Information regarding the estimated depth of the archaeological layers and the height position of the walls respect to the current terrain level has been inferred transforming the levels' point reported by the SCE to a relative reference system where our level 0 coincides with the SCE level 100. The level 100 was chosen as a reference because it is clearly documented in the Section XVII respect to the altar, at the centre of the area, from which the excavation started.

Every depth's layer has been calculated in order to create a database of the measurements for the successive reconstruction of the volumetric stratigraphy (Figure 7). In fact, the successive step consists of positioning the section plans in the exact places (as the original drawings) and from that building the

8 This interpretation was further confirmed by Gjerstad in his supplementary notes to the SCE publication (Gjerstad 1963: 4).

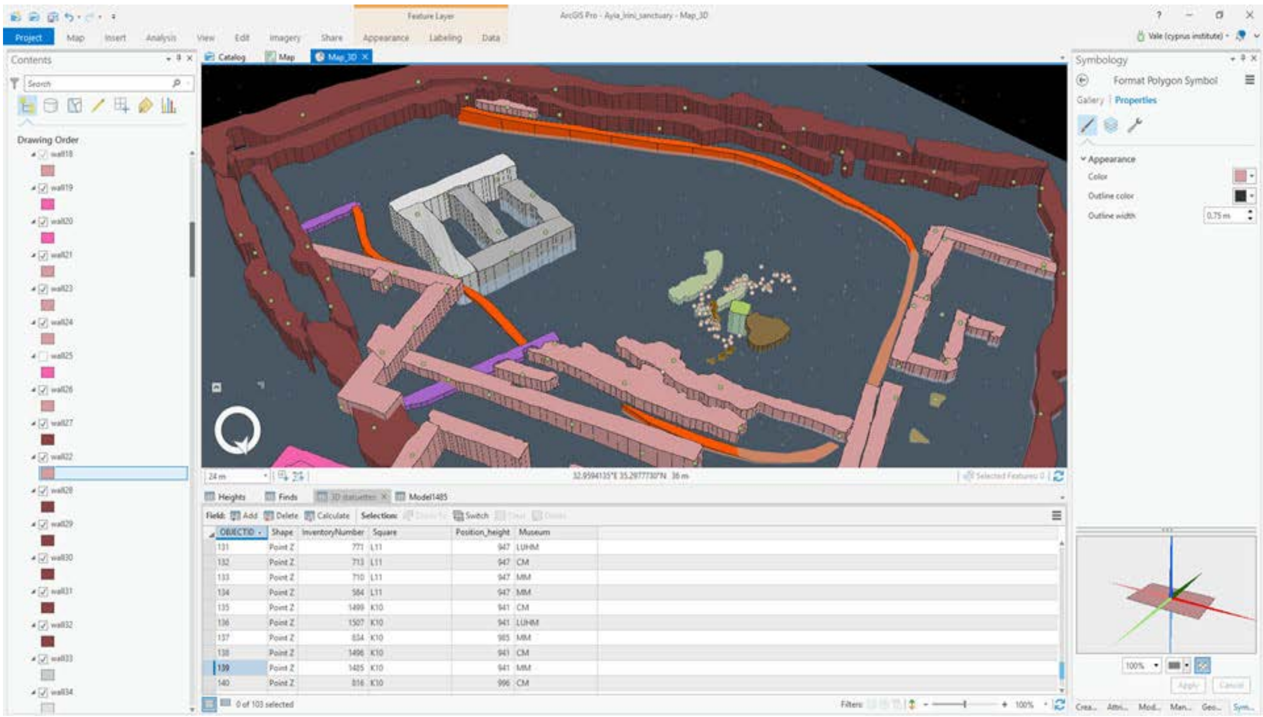

Figure 8. Reconstruction of the excavation: 3D layers and positioning of the 3D finds (Vassallo©).

3D volumes of the layers, where the finds will be integrated and analysed.

Currently, the digital reconstruction of the volumetric layers together with the positioning of the 3D features representing the finds is ongoing (Figure 8). The integration of all this data wants to provide a reconstruction of the original setting in order to better visualize their positions and clarify the different scholars' opinions regarding the presence of natural flooded (how many?) or man-made settings identified/assumed within the excavation.

A recent effort (Vassallo 2016; Vassallo 2017) focuses on 3D semantic and shape based analysis of a sample of finds representing small terracotta statuettes. For that scope, 103 3D models of the artefacts were generated through laser scanning and computer vision.[9] The 3D models of these finds have been imported in the geodatabase together with the other data in order to be visualised and analysed in the virtual environment (Figure 9). For what concerns the rest of the finds, which are not digitized yet[10], we are working at the position of their shapes in the space after the 3D extrusion of their volumes (the SCE provided measurements, positions and height's points for all the material excavated) in order to simulate the space occupied and the interaction with the other elements.

The aim of this work is to reconstruct and visualize the exact position of the finds, in order to visualize their layer more clearly; this would help to get a better view of the number of floods occurred on the site and to understand if they affected, and to what extent, the position of the artefacts. In fact, the archaeological querelle focuses on the existence of two or four floods and the different interpretations of the archaeologists regarding this issue and the stratigraphy in general. As previously mentioned, already among the archaeologists of the SCE there were at that time different options: two floods according to Sjöqvist who excavated the site and four floods according to Gjerstad who published and finally interpreted it.

The SCE archaeologists provided information

9 The 3D models were generated respectively through a NextEngine laser scanner and through the PhotoScan Agisoft software (Verhoeven 2011). The use of the two techniques was done at the beginning for the integration of the two kind of models for a major accuracy. Eventually, after a test it came out that during the 3D shape analysis the different models were able to show different results, all useful to the interpretation of their technical production.

10 Possibly, such work could be realized in the view of a prosecution of the research for a more complete study of the site and its collection.

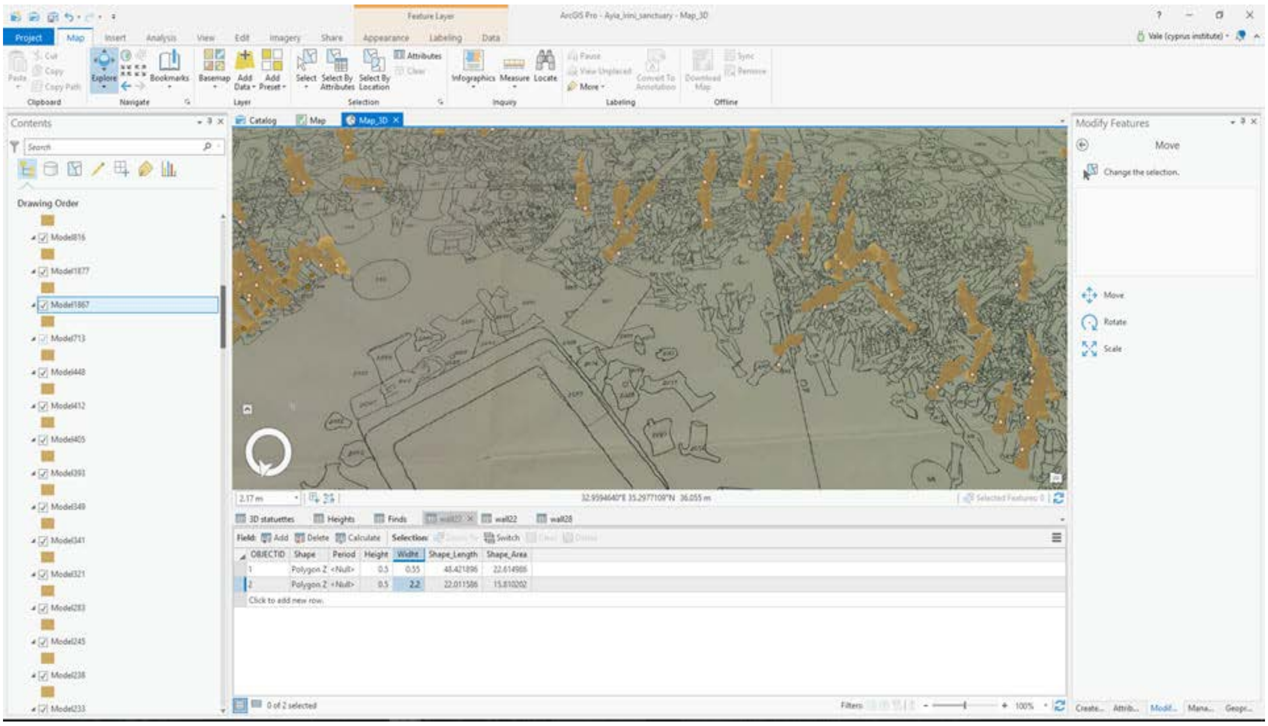

Figure 9. 3D import of the finds in the geodatabase (positions and heights' points have been documented) (Vassallo©).

about the position of each find. The arch. Lindros in his drawings took note of the heights' points of the walls while in the excavation's text the heights' points of each find is given. In the documentation it is not specified where the point of each find is taken (on top of the find? On the terrain where the find laid on?). This is something that we will analyse in the 3D geographical system: the different simulations could help us to visualize the different alternatives.

It is important to highlight that after a closer analysis the SCE Plan XXVIII ('Plan of finds in situ') revealed to be a 'hybrid' between a geometrical plan and an artistic sketch. Indeed, although the altar has the right measurements and position and the finds are documented as belonging to the squares which the excavation was divided into (all these elements have been used to georeference the plan for the integration in the project), many finds do not present exact measurements, they are roughly represented in terms of inclination and in some cases they do not represent the inventoried object.[11] Moreover, the plan is drawn from a frontal perspective. Therefore, if we look at it from another viewpoint, we can see differences in the inclination of the artefacts respect to the terrain and to the other finds.

Another issue is that the arch. Lindros arrived on the site after the excavation of the votive statues and documented them as one assemblage (Westholm 1994: 7-21). Sjöqvist identifies only two floods: one before the artefacts were put in place and another after; he, therefore documents the votives as one assemblage, not disturbed by intermediary floods. This might also be the reason why the plan was taken at the end of the statues' excavation, without any partial plans of the dismantling of the stratified statues. Gjerstad, instead explains the stratification and the periods as a consequence of four floods. In his view, after every flood the older votives were left in situ half covered by the debris, while the newer figures were added on the more recent floor levels, giving evidence of different time periods (Gjerstad et al. 1935). The comparison of all data, such as the inventory numbers list, the old photographs and the plans, will help us to better understand the situation at the moment of the excavation.

A preliminary calculation of the height points of the finds has been performed. This was done to see if a preliminary analysis regarding the relation between the 103 sampled statuettes and the layers' heights could provide any results in the identifi-

11 Like for the interpretative study of the material, more importance is given to the big statues respect to the small ones.

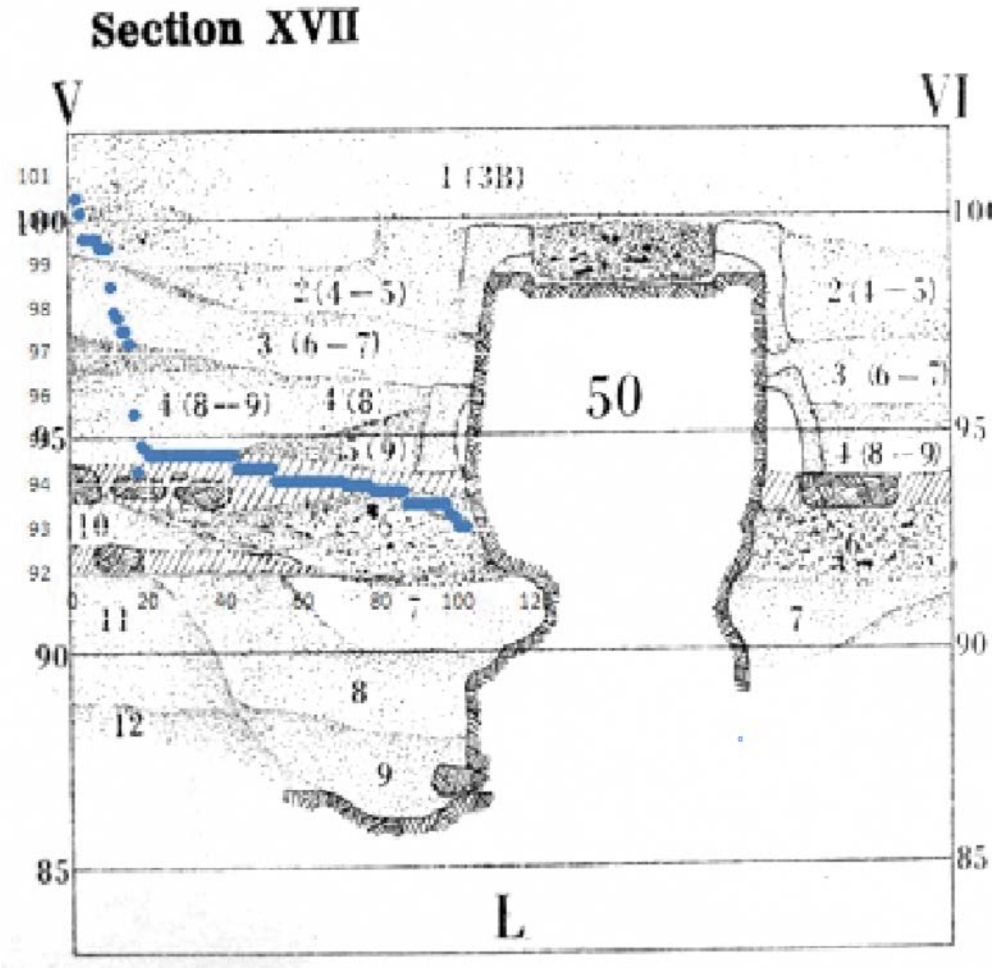

Figure 10. Superimposition of the spatial vertical location of the sampled statuettes on Section XVII (Vassallo©).

cation of specific material settings. It is important to underline that this is a partial calculation and, therefore, a partial reconstructive hypothesis since the test is taking into consideration only the sampled artefacts. On the base of the previous calculation performed on Section XVII (Figure 7) to reconstruct the depth of each layer, the overall archaeological depth is 150 cm; therefore, each unit is equal to 10 cm. The 103 sampled statuettes are included between the height's points 93.1 and 101.0, a space equivalent to 80 cm[12]. A calculation of how many statuettes were found in each unit and their spatial vertical location has been performed. Figure 10 shows the overlap of the resulting statuettes' spatial vertical location on top of the Section XVII, in order to show their distribution within the area considered.

If we look at Figure 10, we notice the following. The z axis distribution of the sampled figurines shows that the vast majority (N=86) are located within a 20 cm range, between relative heights of 93.1 and 94.9. Another possible group of figurines is noted within the range 97.2 and 99.6 (N=13). According to this analysis, we can suggest a main layer of human activity located at the relative height of 94 and apparently a second one, of a much smaller intensity, located ca. 40 cm higher, at the relative height of 98.4.[13] This analysis is made on a partial number of statuettes respect to the whole, but what we can see is the presence of two main archaeological events, which interval is represented by the Layer 4, the only one explicitly identified by the archaeologists as made 'of alluvial sand' respect to the others described as mixed with sand and therefore not clearly and surely identifiable with flooding events (Gjerstad et al. 1935: 663). Additionally, a rarefaction in the positioning of the small statuettes

12 The statuettes measure from a minimum of 20 cm to a maximum of 27 cm.

13 It is important to note that in this assumption no calculation regarding other rotation axis has been done.

Heights' points range	Number of statuettes
100.1 – 101.0	2
99.1 – 100.0	7
98.1 – 99.0	1
97.1 – 98.0	5
96.1 – 97.0	0
95.1 – 96.0	1
94.1 – 95.0	55
93.0 – 94.0	32

Table I: Calculation of the heights' points range on the base of their space occupation and number of the statuettes

towards the more recent periods can be detected.[14] The subdivision seems to suggest therefore two major stratifications that, if not a proof of floods (to be further investigated in the 3D GIS), might advocate for a stratification (chronological or human-based).

Conclusions and Further Steps

The current paper presents the methodological approach, the workflow and the preliminary results aimed at the diachronic reconstruction of the Ayia Irini sanctuary and its finds within a 3D GIS system. The last step of the project regards the reconstruction of the volumetric layers on the base of the Swedish archaeological expedition documentation and the completion of the re-position of the 3D finds within the 3D GIS environment of the sanctuary.

Unfortunately, many archaeological sites excavated in the past suffered of not being sufficiently documented due to different reasons, such as limitation in the technologies or human errors. So far, the analysis in the 3D GIS system made us to identify several issues: inconsistencies within the maps, maps errors, and lack of measurements. Such methodology can help us to overcome such issues and it showed how digital technologies can enhance the overall archaeological process.

The preliminary calculation on the base of the sampled artefacts' distribution seems to show two main human/archaeological events separated by a more natural/geological interval, possibly to be identified with a flood, finally covered by another natural event that caused the abandon of the site.

The final integration of all the volumetric elements and of the finds, beyond serving for the 3D analysis and the final re-assessment of the stratigraphy, it will also work as a main virtual access of the collection for a holistic vision of the archaeological discovery: a 3D spatial context that will give access to the digitally re-unified collection. Since the collection is divided and exhibited in different museums of two countries and the site is currently inaccessible, the 3D space will virtually re-unify the finds and it will be a solution for the context re-interpretation. This can be possibly done thanks to the use of the software package employed: the layers can be easily exported as kmz or kml files that in turn can be viewed by any users (e.g. also general public) in Google Earth. Moreover, it is also easy to transform the resulting map using ArcGIS Online into an app for people to explore online or on their mobile phones, also incorporating historic photos, original scans of field notes, plans and profiles. Therefore, such technical choice on the one hand supports the management of 3D geometrically complex models, and on the other hand opens up options for sharing the resulting data both with other researchers and the public interested to digitally explore the site.

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14 Moreover, the analysis of the statuettes shows a change of typologies towards the upper level of the assemblage respect to the previous ones. Further investigations will help us to understand if the setting of the statuettes follows a chronological pattern. In fact, according to Houby-Nielsen (2016) the setting could also follow a deposition order decided by other criteria than time, such as clusters of similar objects according to different social status or ethnical origin of the worshippers and places of display.

References

Bourogiannis, G, and Mühlenbock, C (eds.) 2016 *Ancient Cyprus Today Museum Collections and New Research*, Åströms förlag, Uppsala.

Burke, P 2001 *Eyewitnessing. The Uses of Images as Historical Evidence*, New York, Ithaca.

Campanaro, D M, Landeschi, G, Dell'Unto, N and Leander Touati, A M 2016 3D GIS for cultural heritage restoration: A 'white box' workflow. *Journal of Cultural Heritage* 18: 321–332. https://doi.org/10.1016/j.culher.2015.09.006

Clark A J and Casana, J 2016 A new use for old photos: archaeological landscape reconstruction in the Big Bend. *Plains Anthropologist*, 61 (240), 469–489. https://doi.org/10.1080/00320447.2016.1245967

De Felice, G and Fratta, A 2016 A Dig in the Archive. The Mertens Archive of Herdonia Excavations: from Digitisation to Communication. In Campana, S, Scopigno, R, Carpentiero, G and Cirillo M (eds.) *Keep the revolution going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, Archeopress, pp. 167-176.

Dell'Unto, N, Landeschi, G, Apel, J, and Poggi, G 2017 4D recording at the trowel's edge: Using three-dimensional simulation platforms to support field interpretation. *Journal of Archaeological Science: Reports* 12: 632–645.

Forte, M (ed.) 2007 *La Vila di Livia. Un Percorso di Ricerca di Archeologia Virtuale*. L'Erma di Breitshneider.

Gjerstad, E, Lindros, J, Sjöqvist, E, and Westholm, A 1935 *The Swedish Cyprus Expedition II (SCE II). Finds and results of the excavations in Cyprus 1927-1931*, Stockholm, pp. 642-824.

Gjerstad, E 1948 *The Swedish Cyprus Expedition IV:2. The Cypro-Geometric, Cypro Archaic and Cypro-Classical Periods*, Stockholm.

Gjerstad, E 1963 Supplementary Notes on Finds from Ajia Irini in Cyprus. *Bulletin of the Medelhavsmuseet* 1963(3): 3-40.

Haggis, D C and Antonaccio, C M (eds.) 2015 *Classical Archaeology in Context. Theory and Practice in the Greek World*, de Gruyter: Berlin/Boston.

Houby-Nielsen, S 2015 *The phantom stratigraphy at Ayia Irini: New investigations into the Swedish excavations in 1929.* Abstract of the Conference "Ancient Cyprus today: Museum Collections and new Research Approaches to the Archaeology of Cyprus", Stockholm 25-27 April 2015.

Houby-Nielsen, S 2016 Excavations at Ayia Irini in the winter of 1929: tricky Phoenicians and Biblical floods. In Bourogiannis, G and Mühlenbock C (eds.) *Ancient Cyprus Today: Museum Collections and New Research.* Åströms förlag. Uppsala 2016, pp. 105-117.

Januarius, J, and Teughels, N 2009 History Meets Archaeology: the Historical Use of Images. A Survey. In: *Revue Belge de Philologie et d'Histoire* 87(3-4): 667-683. www.persee.fr/doc/rbph_0035-0818_2009_num_87_3_7698.

Karageorghis, V, Styrenius, C G, and Winbladh, M L (eds.) 1977 *Cypriote antiquities in the Medelhavsmuseet, Stockholm*, Medelhavsmuseet, Memoir 2.

Landeschi, G, Dell'Unto, N and Ferdani D. 2015 A vector-based pipeline for assessing visibility: a 3D GIS perspective. *Abstract proceedings of the "43rd Computer Applications and Quantitative Methods in Archaeology Conference (CAA 2015)" 30 March - 3 April, 2015, Siena (Italy).*

Landeschi, G, Apel, J, Lindgren, S and Dell'Unto, N 2018 An exploratory use of 3D for investigating a prehistoric stratigraphic sequence In Matsumoto M & Uleberg E *CAA2016: Oceans of Data: Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology, CAA 2016 Oslo, 29 March—2 April 2016.* Archaeopress, *p. 433*

Landeschi, G, Nilsson, B and Dell'Unto, N, 2016a Assessing the damage of an archaeological site: New contributions from the combination of image-based 3D modelling techniques and GIS. *Journal of Archaeological Science: Reports* 10 (2016): 431–440

Landeschi, G, Dell'Unto, N, Lundqvist, K, Ferdani, D, Campanaro, D M and Leander-Touati, A M 2016b 3D-GIS as a platform for visual analysis: Investigating a Pompeian house. *Journal of Archaeological Science*, DOI: 10.1016/j.jas.2015.11.002

Lucas, G 2001 Destruction and the Rhetoric of Excavation, *Norwegian Archaeological Review,* 34:1, 35-46, DOI: 10.1080/00293650119347

Mühlenbock, C and Brorsson, T 2016 ICP-analysis of 66 terracotta statues, statuettes and pottery sherds from Ayia Irini, Cyprus. In Bourogiannis, G and Mühlenbock, C (eds.), *Ancient Cyprus Today: Museum Collections and New Research*. Åströms förlag, Uppsala, pp. 299-312.

Piccoli, C 2016 Enhancing GIS Urban Data with the 3rd Dimension: A Procedural Modelling Approach, in

Campana, S, Scopigno, R, Carpentiero, G and Cirillo M (eds.) *Keep the revolution going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, Archeopress, pp. 815-824.

Poggi, G 2016 Documentation and Analysis Workflow for the On-going Archaeological Excavation with Image-Based 3d Modelling Technique: the Case-study of the Medieval Site of Monteleo, Italy, In: Campana, S, Scopigno, R, Carpentiero, G and Cirillo, M (eds.) *Keep the revolution going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, Archeopress, pp. 369-376.

Richards-Rissetto, H 2017 An iterative 3D GIS analysis of the role of visibility in ancient Maya landscapes: A case study from Copan, Honduras, *Digital Scholarship in the Humanities* 32 (2): ii195–ii212, https://doi.org/10.1093/llc/fqx014

Roosvelt, C H, Cobb, P, Moss E, Olson, B R, and Ünlüsoy, S 2015 Excavation is ~~Destruction~~ Digitization: Advances in Archaeological Practice. *Journal of Field Archaeology* 40, 3.

Sjöqvist, E 1933 Die Kultgeschichte eines Cyprischen Temenos. Beiträge zur Religionswissenschaft, *Archiv für Religionswissenschaft* 30, 309-359.

Vassallo, V 2016 A 3D digital approach to study, analyse and (re)interpret Cultural Heritage: the case study of Ayia Irini (Cyprus and Sweden). In: Campana, S, Scopigno, R, Carpentiero, G, and Cirillo M. (eds.). *Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* Archaeopress. ISBN 9781784913373. pp. 227-232.

Vassallo, V 2017 The archaeological collection of Ayia Irini (Cyprus). A 3D digital approach to analyse and reinterpret a 20th century study. In: Bombardieri, L, Amadio, M. and Dolcetti, F (eds.) *Ancient Cyprus, an unexpected journey. Communities in Continuity and Transition. Proceedings of the PoCA2015 Conference, 25-27 November 2015*, Torino, Italy. Artemide Roma.

Verhoeven, G 2011 Taking computer vision aloft: archaeological three dimensional reconstruction from aerial photographs with photoscan. *Archaeological Prospection*, 18: 67–73.

Westholm, A 1994 The fantastic years on Cyprus. Swedish archaeological excavations in Cyprus, In: Åstrom, P, Gjerstad, E, Merillees R S and Westholm, A (eds.) *The Fantastic years on Cyprus. The Swedish Expedition and its Members*, SIMA Pocket-book 79, Jonsered, pp. 7-21.

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Novel Approaches to the Re-Assembly, Re-Association and Re-Unification of Cultural Heritage Collections – the GRAVITATE Project Solution

Martina Polig
STARC, The Cyprus Institute
m.polig@cyi.ac.cy

Sorin Hermon
STARC, The Cyprus Institute
s.hermon@cyi.ac.cy

Chiara Eva Catalano
MATI-CNR
chiara.catalano@ge.imati.cnr.it

Michela Spagnuolo
MATI-CNR,
michela.spagnuolo@ge.imati.cnr.it

Giusi Sorrentino
STARC, The Cyprus Institute
g.sorrentino@cyi.ac.cy

Stuart E. Middleton
School of ECS,
University of Southampton
sem03@soton.ac.uk

Stefano Modafferi
IT Innovation Centre.
University of Southampton
sm@it-innovation.soton.ac.uk

Abstract

The vast majority of archaeological objects are discovered in a fragmentary state, and the poor state of preservation. Moreover, pieces of historical importance and interest may be dispersed across different collections and museums: accidents, wars, natural disasters, human intervention or the ravages of time, often causes the fragmentation of important art pieces and make their reassembly difficult and even impossible due to missing, eroded parts or different ownerships of fragments of a same object. In other cases objects cannot be reached physically, due to various restrictions, such as storage, permanent exhibition or fragility of their preservation state. The paper will introduce an innovative approach to the R3 challenges that these archaeological problems pose: Re-assembly, Re-association, Re-unification of broken artefacts. The novelty relies on the integration of semantic description and similarity search, based on multi-modal indexing of data and information such as 3D geometry, colour, patterns or features, and non-structured texts. The tools described have been developed by a team of researchers within the EU funded project GRAVITATE. The structure and functionality of the GRAVITATE platform will be showcased through the presentation of real archaeological material, such as the 6th century B.C. Salamis (Cyprus) collection of fragmented terracotta statues, unearthed in Cyprus more than a century ago and since then divided among Cyprus and major UK museums.

Keywords: dispersed cultural heritage, NLP, CIDOC, 3D analysis, 3D visualisation

Introduction

Many encyclopaedic and thematic museums around the globe exhibit artefacts discovered in various parts of the world; for example, the Egyptian museum in Torino is the largest institution exhibiting Egyptian artefacts outside Egypt. Moreover, objects belonging to the ancient Egyptian culture can be found in museums in UK, Germany, France, etc. Many of these objects now populating the exhibit rooms or are filling the storage shelves of museums were brought in decades or even hundreds of years ago, either following purchases, excavations in their countries of origin, donations and so forth. Thus, homogenous collections of artefacts -for example all objects found in a mortuary complex, or all items found within an ancient habitation context or a temple- are now generally distributed among several institutions, either public or private, for exhibiting or educational purposes. It may also happen that different institutions held fragments belonging to the same object, for example one museum holding the head, the other one the torso and the third one the limbs of a large statue. Such objects may never be restored to their original physical appearance, museums being very reluctant to give up pieces from their collection. Also entire collections may never be exhibited together and the provenance of artefacts may get lost and remain orphaned from the original contextualisation point of view.

The picture presented above has another facet as well. Archaeologists working on understanding past societies and their socio-cultural and economic structures look at objects of material culture as a main source of research. They study the shape, production techniques and manufacture process of these objects, within their original context of discovery. Thus, the physical integrity of the object, its relations with other objects and the completeness of the collection are essential and instrumental for assuring a high-quality archaeological research. Thus, many musealised artefacts are not suitable for a systematic and scientific archaeological investigation, given their fragmented condition, the unclear archaeological context and the difficulty in their physical study because of the geographic distribution across continents.

The EU funded project GRAVITATE aims to provide a digital technology based solution to the problems detailed above, addressing the Re-unification of items belonging to the same collection, the Re-association of orphan objects to their initial cultural assemblage, and the Re-assembly of fragmented artefacts. The development of technological solutions is driven by real-world archaeological, conservation, restoration and museological questions and the adopted methodology integrates archaeological research with computer graphics, computer vision, natural language processing and semantic technologies, in order to develop a product that will provide sustainable solutions to the three Rs challenges presented above. The solution proposed by GRAVITATE is a research platform that allows scientists and CH professionals alike to investigate objects looking at their 3D geometry, surface properties, colouring texture and related textual descriptions and semantic information within a single digital environment, where they can conduct 3D shape analysis, features comparison, semantic and 3D annotation, similarity search and so forth, in order to digitally respond to the three Rs challenges.

The main case study of the project is an archaeological collection of about 250 fragments of votive terracotta statues from the ancient city Salamis, on the south-east coast of Cyprus. This collection was unearthed in the 19th century by a British excavation team and is dispersed in various collections in different countries with the majority of the pieces currently being stored in the United Kingdom in the British Museum, the Ashmolean Museum and the Fitzwilliam Museum. The number and the typologies of the complete statues present in the original context has never been established and the task to study the material has been considerably hindered by the dispersion of the material. In the course of the project more datasets were added to represent better the heterogeneity of the archaeological material or to test and develop specific parts of the platform, reaching more than 450 artefacts in total. The two most important additional datasets, which also consist of dispersed material, are pottery fragments from the archaeological collection of Naukratis, an ancient Greek settlement in Egypt, and votive statuettes from the Ayia Irini collection, an important sanctuary on the north coast of Cyprus.

Scientific Approach

The scientific approach of the project revolves around a tight integration of semantics-oriented data and descriptions (e.g., archaeological descriptions or catalogue metadata) with information that can be extracted by 3D geometry processing techniques. This focus on both aspects of cultural heritage artefacts – qualitative textual descriptions and quantitative data and measures – is reflected throughout the development of the platform, which can be used once the

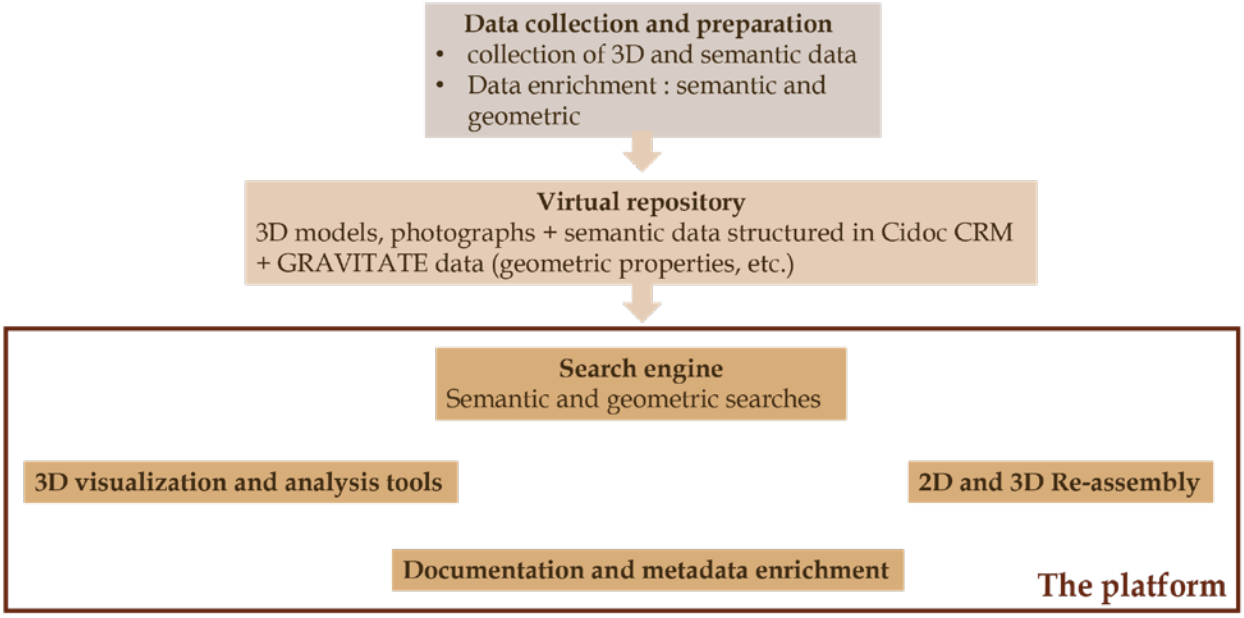

Figure 1. Structure of the GRAVITATE development process.

data in the collections have been properly prepared and organized. The description of the platform will discuss the functionalities and goals of two phases, which in parts ran alongside each other: data collection and preparation with the creation of a repository and the development of the platform itself with its toolsets (Fig.1). The latter includes a semantic and a geometric search-engine, 3D visualisation and analysis tools, 3D re-assembly and metadata enrichment tools.

Data Collection and Preparation

The data collection and preparation phase consisted in collecting museum records and archaeological descriptions of the GRAVITATE datasets on the semantic side, and in the 3D digitization of the artefacts on the geometric side. Since the metadata from the different museums did not follow the same scheme, it was necessary to bring all the information on the same level and into the same ontological system. All the available information was mapped into the British Museum scheme, which extends CIDOC Conceptual Reference Model (CRM) scheme (Doerr 2003), and then codified in RDF, a language that describes information in a form that can be processed by computers (McBride 2004).

The 3D digitization of the artefacts was carried out using photogrammetry and two different kinds of close range scanners: the NextEngine and the Aicon SmartScan. The colour information of the artefacts was encoded on the vertices of the 3D models by manual alignment of colour calibrated photographs using the software MeshLab (Cignoni et al. 2008). The 3D models were then run through a cleaning pipeline, named GRAVIfix, specifically designed for the GRAVITATE project to ensure that the models meet the requirements of the algorithms integrated in the platform (Mortara, Pizzi and Spagnuolo 2017).

Another important data preparation step was faceting (Fig.2), that is, the semi-automatic distinction of the skin of an artefact and its fracture (El-Naghy and Dorst 2017). This is particularly important for methods that address the three Rs problems.

Moreover, to reduce the computational effort for some of the algorithms employed in the next stage of data preparation and in the platform itself and for 3D web visualisation, several resolutions of the 3D models (1M, 100K and 50K) were generated. This required to develop a method to transfer the geometry of selected areas (for faceting and part-based annotation , see below) from one resolution to another in an automatic and accurate way (Scalas, Mortara and Spagnuolo 2017).

The next phase of data preparation consisted in semantic and geometric data enrichment which serves for different purposes, such as enhanced visualisation or search. Where and when this enriched

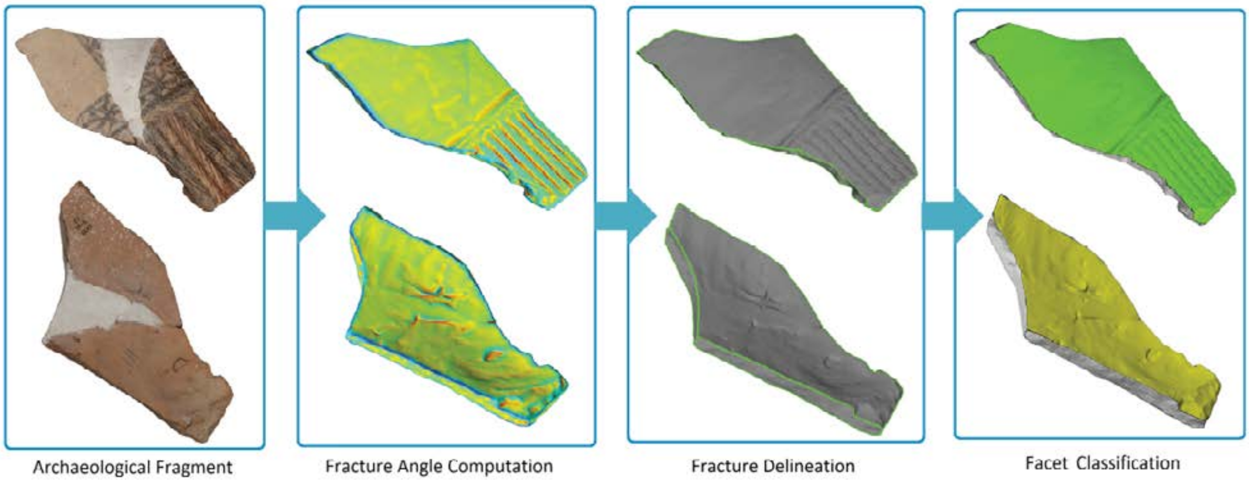

Figure 2. Automatic computation of the facets on an artefact. ElNaghy and Dorst 2017.

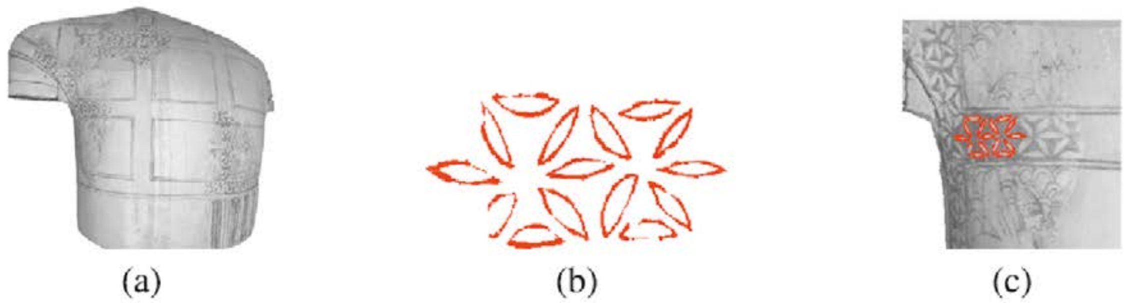

Figure 3. Automatic recognition of flower pattern based on curve approximation. (Torrente, Biasotti and Falcidieno 2018).

data comes into play will be discussed with the single functionalities. An extensive description of the methods and results in the data preparation process is not within the scope of this paper and are elucidated in the respective publications.

In terms of semantic data enrichment, free text descriptions of the single pieces in the collections were analysed with Natural Language Processing (NLP) techniques to extract new semantic information. The curated metadata were enriched by a novel algorithm based on Open Information Extraction (Christensen et al. 2011), extracting additional metadata from artefact physical descriptions. For the geometric enrichment, various properties of the 3D models were calculated, which include the prevalent thickness based on the shape diameter function (SDF) (Shapira, Shamir and Cohen-Or 2008) or different ways to quantify the curvature, for example through the shape index (Koenderink and van Doorn 1992) or the mean curvature. Some of these geometric properties were also processed further to define collection-specific feature extraction modules, such as eyes or relief decorations (Biasotti et al. 2017; Torrente, Biasotti and Falcidieno 2018).

The collected and newly generated information is being stored in a virtual repository based on RDF triples, which contains: 3D models and photographs, semantic metadata in the CIDOC CRM scheme and the new semantic and geometric information from the data enrichment phase.

Development of GRAVITATE Toolsets

The Search Engine

All this data needs to be made accessible and searchable in order to be able to retrieve information of interest and make connections between different objects in the database. Thus, the GRAVITATE

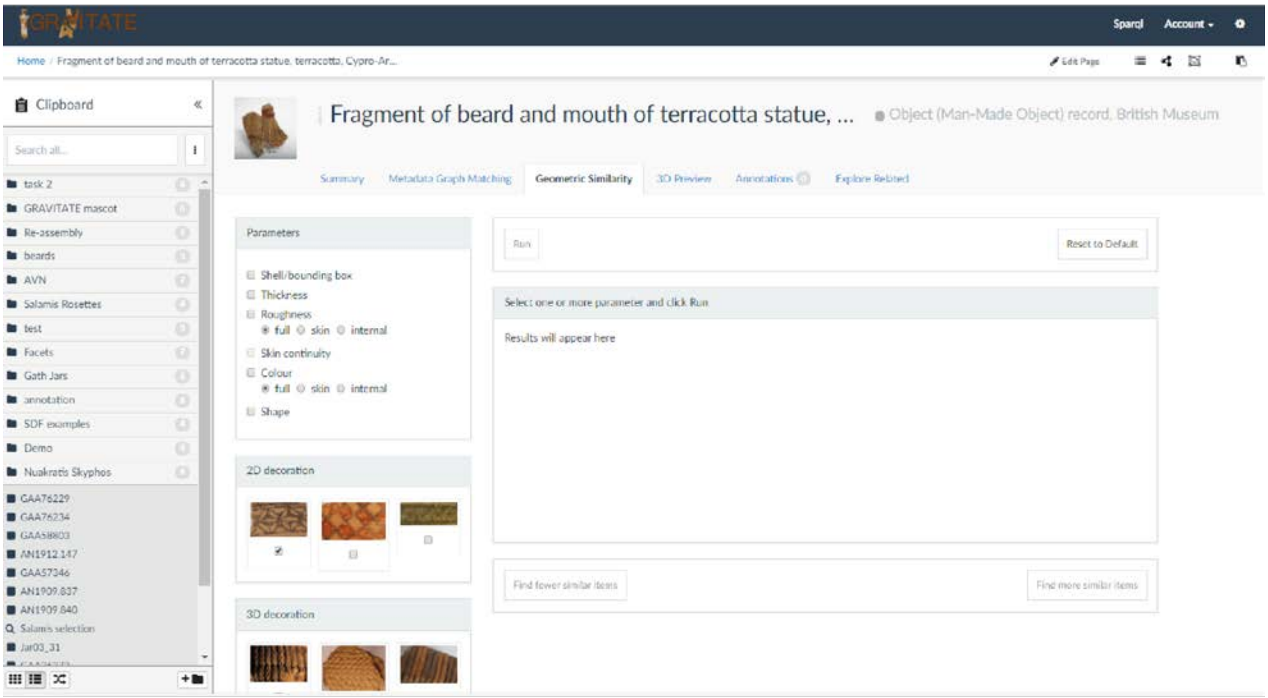

Figure 4. Geometric Similarity search in the web-client.

platform was equipped with a sophisticated search engine that allows to perform both semantic and geometric queries, which is particularly novel and interesting.

The starting point of such a query is an artefact of interest and the aim is to find other pieces that share with the query one or a combination of similar characteristics chosen by the user. On the semantic side, the similarity search is based on graph matching. We used a RDF2VEC graph embedding technique (Ristoski and Paulheim 2016) to perform query by example, using the query artefact metadata as the basis for similarity. A user is able to look for objects that have similar material, type, decoration, production time and place, symbol and physical features.

The geometric search is based on a set of descriptors computed for each artefact and distances that evaluate the similarity between two artefacts as the distance between their descriptors. Given the query artefacts, the geometric search permits to look for objects that have a similar overall shape, size, colour, or roughness as well as a similar 2D or 3D decoration (for the retrieval of 3D patterns (see Biasotti et al. 2018). As most of the fragments exhibit a different appearance on the external and internal facets (e.g. colour, roughness) it is possible to improve search results by restricting the search to the pertinent side of a fragment (see Fig.4).

3D Visualisation and Analysis Tools

Most of the geometric information computed during the geometric enrichment phase are used to build the descriptors that are needed to run the geometric search. However, their value is not limited to the search engine: the geometric data are indeed useful also for direct inspection, visual comparison and analysis, using 3D models as simulacra of the real artefacts. Thus, 3D visualisation and analysis tools for the comparison of 3D models and the visualisation of geometric properties were developed in the platform (see Fig.8).

3D-Reassembly

In the case of a discovery of potential matches between fragments, identified for example with the combined search engine, a semi-automatic 3D re-assembly tool was developed building on the experience of the PRESIOUS (Predictive digitization, restoration and degradation assessment of cultural heritage objects) project (Savelonas et al. 2017). In our approach the fracture facet of a fragment is

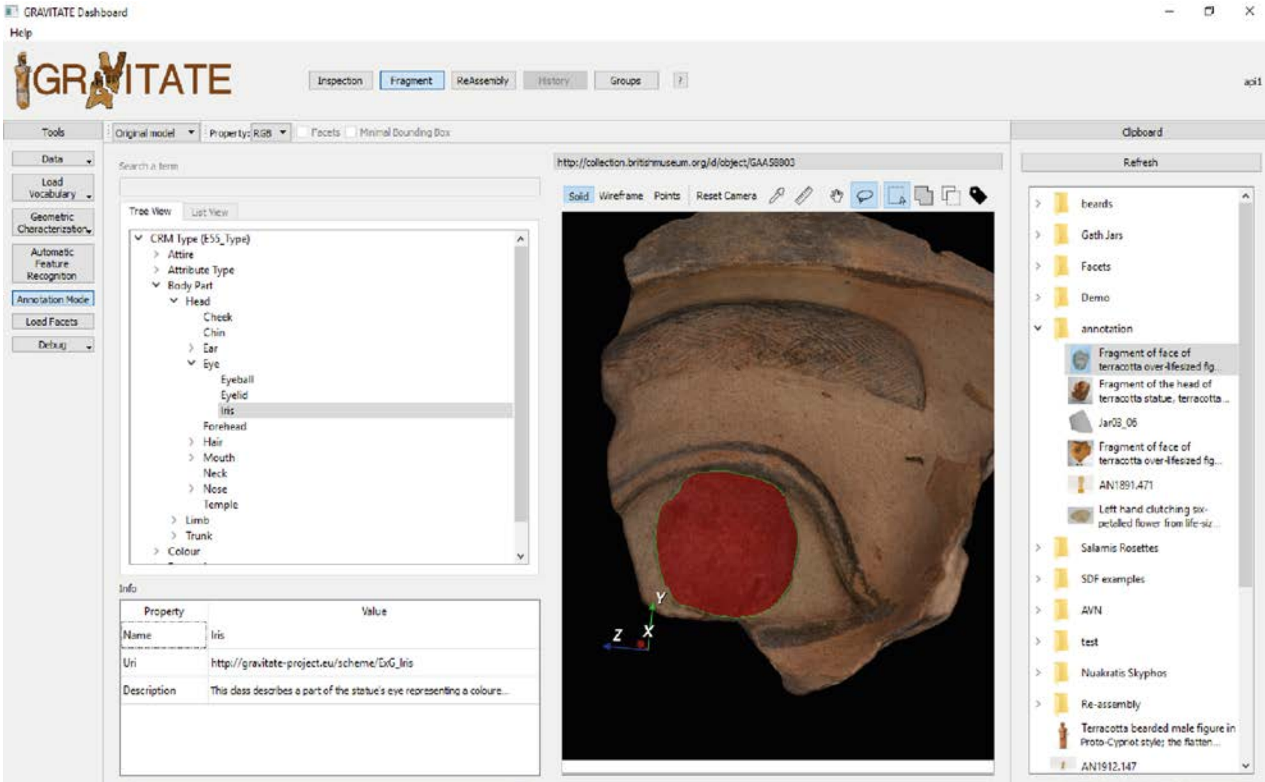

Figure 5. 3D annotation of the iris of a fragment in the desktop-client.

detected and principal directions and curvatures are computed. Then, the algorithm looks for compatibility of curvatures between a set of previously selected fragments, attempting re-assembly and suggesting aligned pairs to the user. A fine alignment of this initial rough positioning of pairs of fragments is being developed based only on the geometry of the fracture surfaces. The problem of potentially missing geometry due to abrasion or other type of damages to the fractures is being addressed through a simplification of the fracture surfaces using mathematical morphology operations (ElNaghy and Dorst 2018).

Metadata Enrichment

In order to make the knowledge and information content of the system dynamic, the platform contains also different possibilities to enrich the metadata in various ways. Observations that concern directly the geometry of artefacts can be annotated in 3D through the selection of the area of interest and tagging it with an appropriate term from a specifically designed Cultural Heritage Artefact Partonomy (CHAP) (see Fig.5). Such vocabulary has been defined starting from the archaeological description of the artefacts of the Salamis, Naukratis and Ayia Irini datasets studied in the project. Moreover, the annotated features can be suitably measured, enriching the semantic annotation with quantitative values to be used in archaeological research. The geometry of this area receives thus a direct semantic link and meaning, codified in RDF, as the metadata of the respective artefact (Catalano, Repetto and Spagnuolo 2017). There is also the possibility to enrich the metadata by adding information to the traditional CIDOC CRM metadata scheme for observations that are not directly linked to the geometry (e.g. provenance, dating, material, etc.). Every intervention is documented and has to be motivated making the process transparent and traceable, enabling a dialogue between different users of the platform.

The Platform Interface

The interface of the platform is divided in two clients: a web-client and a desktop-client. This division is the consequence of the intrinsic limitations of

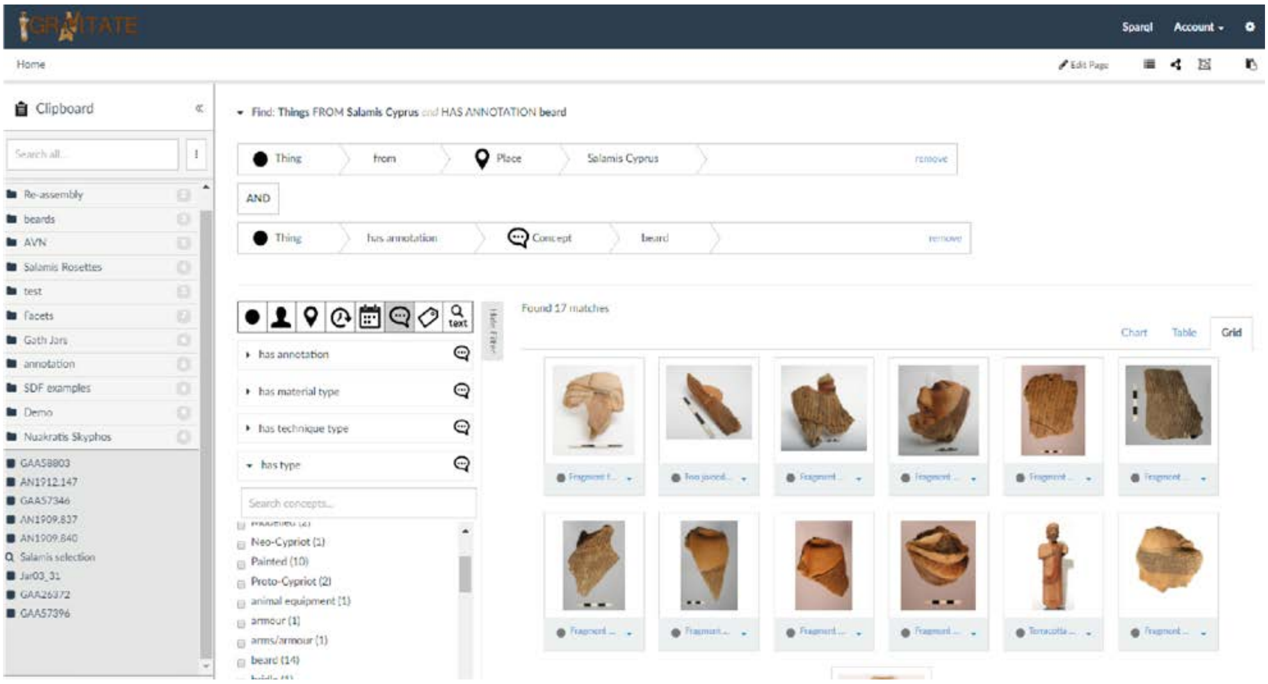

Figure 6. Query in the web-client looking for objects from Salamis that are or have a beard.

web-browsers to deal with high resolution 3D models in a fast and efficient way and the need to use the web for the GRAVITATE semantic search-engine. The latter is in fact largely based on ResearchSpace, a collaborative semantic web environment developed by the British Museum that works entirely from the web (Tanase and Oldman 2018). It was adopted by GRAVITATE and modified to adapt it to its needs. The main purpose of the web-client is to explore and browse the database for objects of interest and to provide useful information on the pieces. The desktop-client on the other hand serves mainly for the manipulation and visualisation of high resolution 3D models (Catalano, Repetto and Spagnuolo 2017). The two clients are synchronised through a clipboard, in which objects of interests can be stored and grouped by the user.

The Web-Client:

More specifically the web-client contains the search engine that permits access to the repository. It is divided in a work-space and the clipboard where objects of interest can be saved and grouped. In the work-space queries can be composed in a versatile highly adaptive manner using concepts derived from CIDOC CRM and can be further refined through filters (Fig.6). The user can select two key concepts (Actor, Place, Event, Thing, Time, Concept and Class) and define the relationship between them (e.g. search for a Thing from a specific Place).

Search results can be browsed and single objects explored in more detail by looking at their metadata, photographs and a preview of its 3D model (Fig.7). In the metadata display the previously mentioned metadata enrichment that is not based on geometry takes place. A user can add more information to the different CIDOC CRM metadata categories (e.g. material, type) and express an opinion on the already available information. Once one object is selected, it is also possible to look for similar objects by conducting the semantic or geometric similarity searches.

The Desktop-Client:

If a user wishes to explore selected artefacts in more depth, (s)he can move to the desktop-client, where the clipboard contains the same objects that were selected and grouped together in the web-client. The desktop-client is also divided in the clipboard and a workspace as well as a toolbar and a viewbar. The latter determines the kind of activity a user can per-

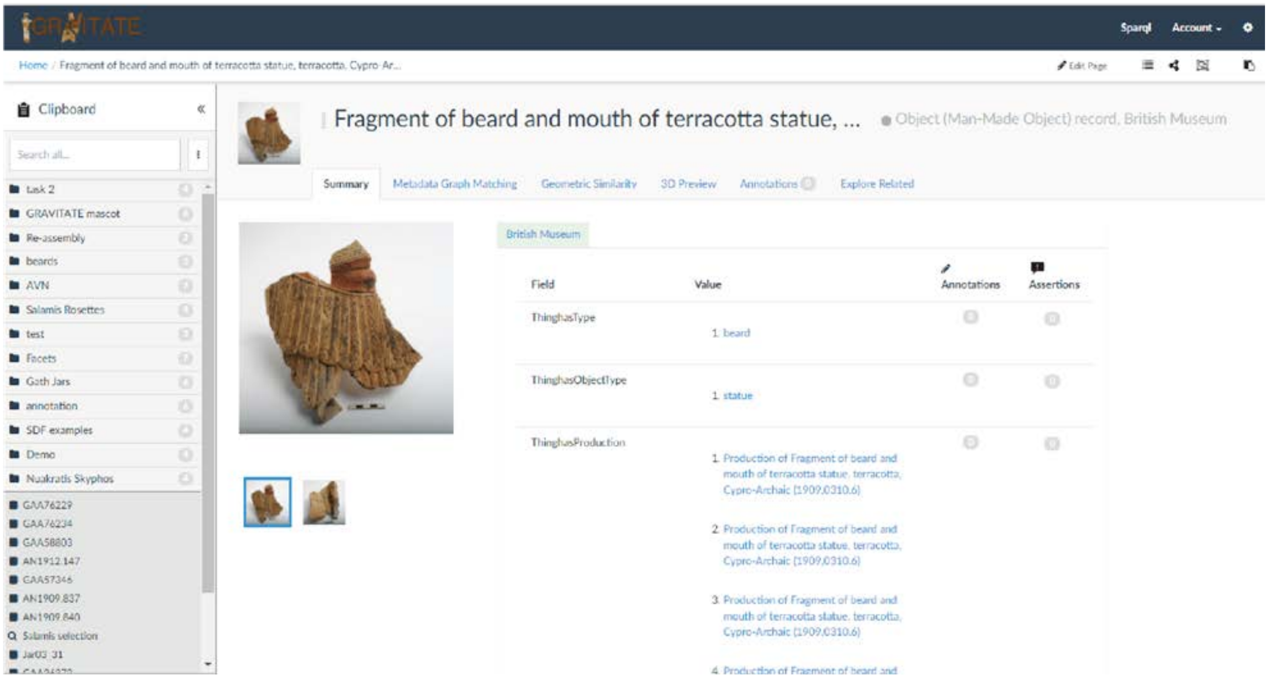

Figure 7. Looking at the metadata of an artefact in more detail in the web-client.

form and what tools are available and consists in: Inspection View, Fragment View, Re-Assembly View, History View and Groups View.

The Inspection and Fragment View contain a standard visualisation and manipulation tool for rotation, zoom in and out, measurement, changing the light position and change the visualisation mode between points, wireframe and solid. The metadata and paradata of each artefact are displayed as an expandable tree below the interactive 3D canvas. In the Inspection view, geometric properties, facets and annotations of the displayed artefacts can be loaded as well and being inspected in parallel for two or more artefacts (Fig. 8).

The Fragment View has the annotation tool, which allows a user to select a specific area on the model and create a new 3D part-based annotation with the developed CHAP vocabulary. If the user has discovered artefacts that might match physically and can be reassembled, (s)he can move to the Re-assembly View. The potentially matching objects are put in a workbench by the user and the reassembly algorithms will attempt to find matching pairs, which the user can approve or discard. All the steps taken and observations made can be documented in the History view. Finally, the Groups View is used to manage the groups of artefacts made in the clipboard.

The 3 Rs and the Platform – Workflows and Use of the System

The Re-unification of dispersed collections in a digital repository, made accessible through a platform that allows to perform also Re-associations and Re-assemblies, enables to ask archaeological questions that previously could only be addressed with difficulty. The research questions and objectives we identified relate to the exploration and classification of a dataset, the study of style and of production techniques within or across collections and the understanding of archaeological context. Furthermore, the system can be used for a systematic enrichment of the metadata.

The Salamis collection provided a good example where the platform helped to understand the material (what type of statues are present in the collection) and attempt a classification. In this process the web-client was used for a semantic exploration of the dataset in order to create meaningful groups of fragments that can be associated. The semantic and geometric similarity searches play an important

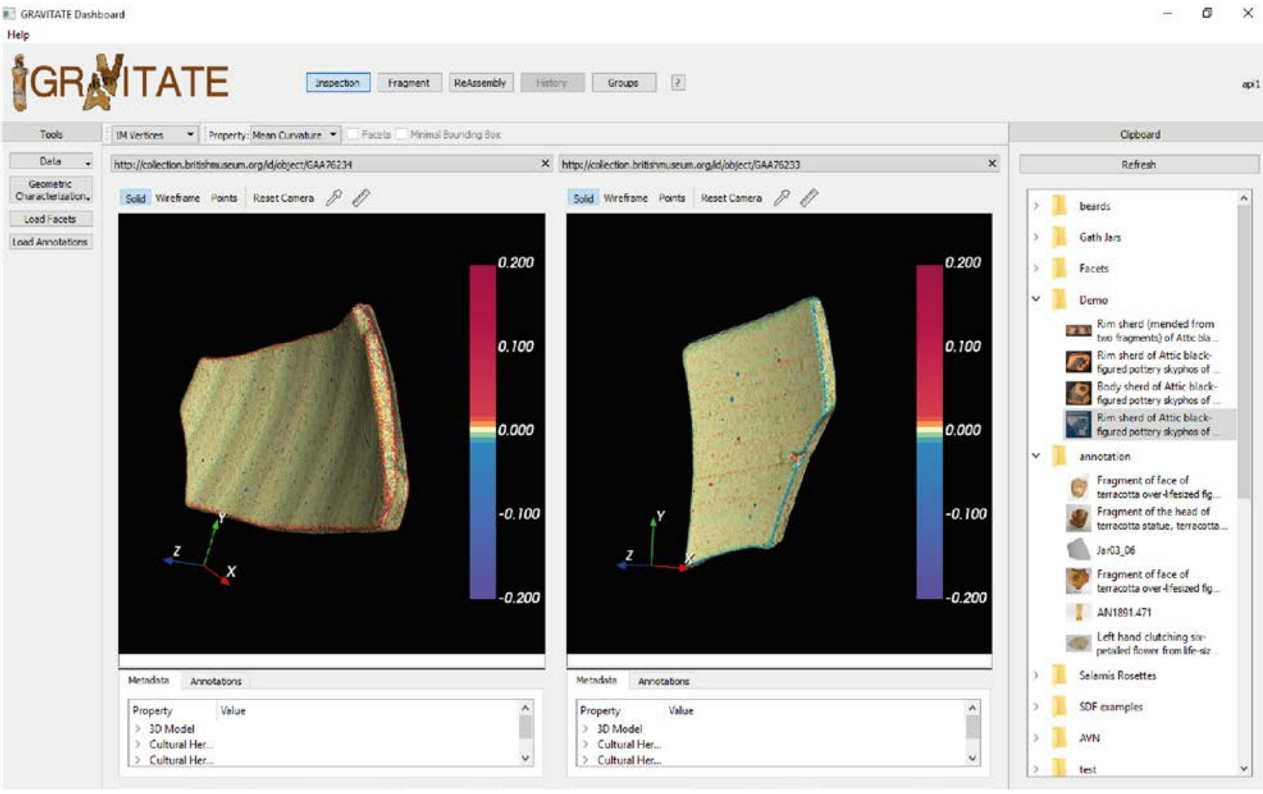

Figure 8. Visualisation and comparison of the mean curvature on two fragments in the desktop-client.

role here, allowing a user to find similar artefacts faster. On some occasions it might even be possible to attempt a reassembly of a few fragments to understand better the shape and dimension of the statue the pieces belonged to. In other cases, re-assembly can help understanding the archaeological context: by reassembling a group of fragments found in the same context, even if their typology is known, we may understand how many complete objects there were originally. Knowing how many objects of a certain type were in a context facilitates its interpretation.

The study of style uses the re-association capabilities of the platform. In the first step this happens in the web-client through the different possibilities to conduct queries and then, in a second step, in the desktop-client, taking measurements and observing subtle differences between elements and features of interest that point to stylistic influences and developments. In this context, it may be particular useful to create also 3D annotations to enrich the metadata together with the exact measurements of the interesting areas, and make future queries more effective and accurate.

Also the investigation of production techniques may be accomplished through the 3D visualisation and analysis tools in the desktop-client. The mean curvature and shape index calculated on the high resolution models as well as the enhanced visualisation of features and the possibility to make measurements allow to study signs of production on artefacts, such as manufacturing lines in the internal face of a sherd (see Fig.8).

The system was designed to be open only to people authorized by an administrator and requires a login to access and use it. This is a deliberate choice to address right issues revolving around data, since the system allows both the access and manipulation of it. In terms of use, there is no predefined workflow of the platform, allowing a user to begin, stop and continue working at any time and place in the system. To illustrate the usage of the platform, the typical workflow begins in the web-client, where the user looks for artefacts relevant for a particular archaeological question. This reasoning process can be accompanied by a deeper analysis and annotation of the high-resolution 3D models in the desktop-client. It may or may not include the use of the Re-assembly tool, and may be followed by the return to the web-client either to look for other artefacts or to conduct a different semantic or geometric search.

Conclusions

The aim of the project was to propose solutions to three cultural heritage challenges: Re-unification, Re-association and Re-assembly. The problem of Re-unification was addressed by bringing dispersed material together in one digital repository. The different tools allowing to explore the repository as well as the tools dedicated to the analysis of the 3D models enable to create and discover meaningful connections between artefacts in the repository and thus answer to the issue of Re-association. Finally, the problem of Re-assembly was addressed through the development of a semi-automatic tool for matching fragments.

There are still many potential developments for the platform. Some elements, such as the 3D reassembly or the semantic graph matching, can still be improved and deserve further attention. Other research lines which were pursued in the project did not reach a stage in which it was possible to integrate them in the platform, but show great potential and merit future work. These include tools for 2D re-assembly (Paikin and Tal 2015), or a 3D re-assembly based on a template for the refitting of fragments that belong to the same object but do not present common fracture surfaces.

A platform like GRAVITATE is capable of hosting the entire workflow necessary when studying a cultural heritage collection, from browsing a museum catalogue in search of pieces of interest to the inspection and study of the objects themselves. The environment has been designed to maintain the connection between the semantic and the geometric data and to be transparent, open and dynamic, enabling the exchange of ideas and interpretations through the continuous enrichment of the underlying metadata and the accurate measurements of geometric and colorimetric properties of the 3D high-res models. The biggest challenge for the adoption of such a system lies in the ingestion phase, that is the creation and preparation of the necessary data, which requires the mapping of semantic data into the CIDOC CRM scheme and the availability of the dataset in high quality 3D models. In a wider perspective, the issue of the federation of the repositories of different museums should be tackled to guarantee the share of knowledge among the institutions, while preserving the specific organisation of the individual digital archives. Indeed, the Cultural Heritage sector has already made considerable efforts towards a common way of structuring and storing of metadata and a mass digitization of cultural heritage objects. It is possible to observe the latter in initiatives such as CultLab3D, led by the Fraunhofer Institute for Computer Graphics Research IGD, which developed an automated 3D capture pipeline (Santos et al. 2017). In terms of communal data structure and storage, we can mention, among others, the ARIADNE project, which aims at providing e-infrastructure to collect, share and access heterogeneous data created across various institutions and countries (Meghini et al. 2017; Niccolucci and Richards 2019) and was recently extended within the ARIADNEplus initiative.

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References

Biasotti, S, Moscoso Thompson, E, Aono, M, Ben Hamza, A, Bustos, B, Dong, S, Du, B, Fehri, A, Li, H, Limberger, F A, Masoumi, M, Rezaei, M, Sipiran, I, Sun, L, Tatsuma, A, Velasco-Forero, S, Wilson, R C, Wu, Y, Zhang, Y, Zhao, T, Formasa, F and Giachetti, A 2017 Shrec'17 Track: Retrieval of surfaces with similar relief patterns. In: *10th Eurographics Workshop on 3D Object Retrieval.* April 2017 Lyon, France.

Biasotti, S, Thompson, E M, Bathe, L, Berretti, S, Giachetti, A, Lejemble, T, Mellado, N, Moustakas, K, Manolas, I, Dimou, D, Tortorici, C, Velasco-Forero, S, Werghi, N, Polig, M, Sorrentino, G and Hermon, S 2018 SHREC'18 track: Recognition of geometric patterns over 3D models. In: *Eurographics Workshop on 3D Object Retrieval.* 2018 p. 9.

Catalano, C E, Repetto, A and Spagnuolo, M 2017 A Dashboard for the Analysis of Tangible Heritage Artefacts: a Case Study in Archaeology. In: *15th EUROGRAPHICS Workshop on Graphics and Cultural Heritage.* The Eurographics Association. DOI: https://diglib.eg.org:443/handle/10.2312/gch20171307

Christensen, J, Mausam, Soderland, S and Etzioni, O 2011 An analysis of open information extraction based on semantic role labeling. *K-CAP 2011 ACM Press*. p. 113. DOI: https://doi.org/10.1145/1999676.1999697

Cignoni, P, Callieri, M, Corsini, M, Dellepiane, M, Ganovelli, F and Ranzuglia, G 2008 MeshLab: an Open-Source Mesh Processing Tool. In: Scarano, V, De Chiara, R, and Erra, U (eds.) *Eurographics Italian Chapter Conference 2008,* pp. 129–136.

Doerr, M 2003 The CIDOC Conceptual Reference Module: An Ontological Approach to Semantic Interoperability of Metadata, *AI Magazine*, 24(3): 75.

ElNaghy, H and Dorst, L 2017 Geometry Based Faceting of 3D Digitized Archaeological Fragments. In: *October 2017 IEEE*, pp. 2934–2942. DOI: https://doi.org/10.1109/ICCVW.2017.346

ElNaghy, H and Dorst, L 2018 Using Mathematical Morphology to Simplify Archaeological Fracture Surfaces. In: *Symposium on Geometry Processing 2018 - Posters*. The Eurographics Association. DOI: https://doi.org/10.2312/sgp.20181179

Koenderink, J J and van Doorn, A J 1992 Surface shape and curvature scales, *Image and Vision Computing*, 10(8): 557–564. DOI: https://doi.org/10.1016/0262-8856(92)90076-F

McBride, B 2004 The Resource Description Framework (RDF) and its Vocabulary Description Language RDFS. In: Staab, S and Studer R. (eds.) *Handbook on Ontologies. International Handbooks on Information Systems*. Springer, Berlin, Heidelberg. pp. 51–65. DOI: https://doi.org/10.1007/978-3-540-24750-0_3

Meghini, C, Niccolucci, F, Felicetti, A, Ronzino, P, Nurra, F, Papatheodorou, C, Gavrilis, D, Theodoridou, M, Doerr, M, Tudhope, D, Binding, C, Scopigno, R, Vlachidis, A, Richards, J, Wright, H, Geser, G, Cuy, S, Fihn, J, Fanini, B and Hollander, H 2017 ARIADNE: A Research Infrastructure for Archaeology, *Journal on Computing and Cultural Heritage*, 10(3): 1–27. DOI: https://doi.org/10.1145/3064527

Mortara, M, Pizzi, C and Spagnuolo, M 2017 Streamlining the Preparation of Scanned 3D Artifacts to Support Digital Analysis and Processing: the GRAVITATE Case Study. In: *15th EUROGRAPHICS Workshop on Graphics and Cultural Heritage 2017*, p. 5.

Niccolucci, F and Richards, J 2019 The ARIADNE Impact. Hungary: *ARCHAEOLINGUA FOUNDATION*. DOI: https://doi.org/10.5281/zenodo.3476712

Paikin, G and Tal, A 2015 Solving multiple square jigsaw puzzles with missing pieces. *The IEEE Conference on Computer Vision and Pattern Recognition, June 2015*, pp. 4832–4839. DOI: https://doi.org/10.1109/CVPR.2015.7299116

Ristoski, P and Paulheim, H 2016 RDF2Vec: RDF Graph Embeddings for Data Mining. In: Groth, P., Simperl, E., Gray, A., Sabou, M., Krötzsch, M., Lecue, F., Flöck, F., and Gil, Y. (eds.) *The Semantic Web – ISWC 2016*. Cham: Springer International Publishing. pp. 498–514. DOI: https://doi.org/10.1007/978-3-319-46523-4_30

Santos, P, Ritz, M, Fuhrmann, C and Fellner, D 2017 3D mass digitization: a milestone for archeological documentation, *Virtual Archaeology Review*, 8(16): 1. DOI: https://doi.org/10.4995/var.2017.6321

Savelonas, M A, Andreadis, A, Papaioannou, G and Mavridis, P 2017 Exploiting Unbroken Surface Congruity for the Acceleration of Fragment Reassembly. In: *Eurographics Workshop on Graphics and Cultural Heritage 2017*, The Eurographics Association. DOI: https://doi.org/10.2312/gch.20171305

Scalas, A, Mortara, M and Spagnuolo, M 2017 3D Annotation Transfer. In: *15th EUROGRAPHICS Workshop on Graphics and Cultural Heritage 2017*, The Eurographics Association. DOI: https://doi.org/10.2312/gch.20171295

Shapira, L, Shamir, A and Cohen-Or, D 2008 Consistent mesh partitioning and skeletonisation using the shape diameter function, *The Visual Computer*, 24(4): 249–259. DOI: https://doi.org/10.1007/s00371-007-0197-5

Tanase, D and Oldman, D 2018 Reshaping the Knowledge Graph by connecting Researchers, Data and Practices in ResearchSpace. In: *Proceedings of the 17th International Semantic Web Conference 2018.*

Torrente, M-L, Biasotti, S and Falcidieno, B 2018 Recognition of feature curves on 3D shapes using an algebraic approach to Hough transforms, *Pattern Recognition*, 73: 111–130. DOI: https://doi.org/10.1016/j.patcog.2017.08.008

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Florian Thiery & Allard Mees
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Taming Ambiguity - Dealing with Doubts in Archaeological Datasets using LOD

Florian Thiery
Department of Scientific IT
Leibniz-Zentrum für
Archäologie (LEIZA)
florian.thiery@leiza.de

Allard Mees
Department of Scientific IT
Leibniz-Zentrum für
Archäologie (LEIZA)
allard.mees@leiza.de

Abstract

The Linked Data Cloud is full of controlled resources, which quality is in fact difficult to handle. Firstly, each resource collection, e.g. a thesaurus, is cooking its own soup related to its research context. Secondly, conceptualisation of Linked Open Data (LOD) assumes standardised data, but in reality, either generic concepts or real instances exist. Thirdly, archaeological items are usually related to generic instances in the LOD cloud, based on their object oriented nature. Describing these relations by modelling archaeological assumptions causes ambiguities which have to be tamed in order to guarantee data quality which can be reused. In this paper we will demonstrate this in three examples from the databases of the Römisch-Germanisches Zentralmuseum Mainz and are proposing ways to solve the handling of ambiguities with a software framework called Academic Meta Tool (AMT).

Keywords: Linked Open Data; graph modelling; ontology; vagueness; uncertainty

Introduction

Archaeological research implicitly deals with doubts and ambiguities in data modelling, aiming to overcome them. Creating reproducible and comprehensible data for the purpose of re-use, whilst also guaranteeing data quality in archaeological data, involves disclosing any doubts and ambiguities. This could be done in any data modelling strategy, e.g. relational or graph based modelling as Linked Open Data (LOD) defined by Berners-Lee (2006).

The Römisch Germanisches Zentralmuseum in Mainz (RGZM) is increasingly engaged with the topic of LOD and aims to provide transparent data to achieve interoperability. In order to achieve this, the RGZM is setting up a 'central metadata index' for aligning its various specialised distributed databases. In this context, it is trying to control the doubts and ambiguities and model them semantically. Data and implicit knowledge from these databases will be modelled as LOD.

A considerable amount of archaeological objects are bearing figural representations (e.g. humans, animals, plants). In the case of identifying these iconographical items, ambiguities may appear. These ambiguities are often combined with doubts. With regards to 'doubts', and trying to model them, we have to consider that two different types of doubts exist: 'uncertainty' and 'vagueness' (Unold et al. 2017).

Moreover, in archaeological research deploying LOD, normally authoritative repositories and controlled vocabularies are used, suggesting that we create a fixed 'undoubted anchor' in the LOD Cloud in order to enable the usage of this resource as a central node. Each resource collection is biased to its own research context, e.g. the Getty Art and Architecture Thesaurus (Getty AAT) (J. Paul Getty Trust 2017) or the Heritage Data (2013) vocabularies like the 'FISH Archaeological Sciences Thesaurus' (FISH 2018a). Because the LOD Cloud is full of isolated resource collections which are build according to research community specific criteria, the LOD anchoring runs rapidly out of control.

Archaeological items are usually related to generic instances in the LOD Cloud based on their object oriented nature. These relations are described by modelled archaeological assumptions, regularly causing ambiguities which have to be tamed to guarantee data quality and ensure the data can be reused.

In this paper we propose a solution for taming the doubts and ambiguities in LOD using a software framework called Academic Meta Tool (AMT) by Thiery and Unold (2018a). We continue the more theoretical work already done (Tolle and Wigg-Wolf 2015; Bruhn et al. 2015) by providing a low-threshold generic web-based software tool, which enables researchers to define their own research specific ontology, describing vague relations in graphs. On top of this, AMT is able to do reasoning according user defined ontology rules.

After a general introduction to the handling of modelling doubts in the Digital Humanities (DH), LOD, and graphs (cf. section 2), the theoretical concepts of uncertainty and vagueness in graphs are presented (cf. section 3). This is followed by some use cases for doubtful statements in relational database management systems (RDBMS) and LOD (cf. section 4). The actual software tool AMT involved is being discussed (cf. section 5) and some examples of its usage in the context of databases at the RGZM are demonstrated (cf. section 6).

Modelling Doubts

This section gives a short overview on data modelling in the DH using relational RDBMS, NoSQL, including graph structures. Within archaeology, semantic LOD modelling has gained increasingly acceptance. But the problem of modelling doubts has not been solved yet. A possible way to tackle this is discussed below.

Data Modelling in the DH

Data modelling in the DH has changed considerably throughout the last few decades. In the first phase of web-based databases in the mid-1990s, common rigid RDBMS in software such as Microsoft Access, Oracle, Informix, MySQL or FoxPro were considerably popular (Beagrie 1993). Some databases at the RGZM, funded by the European Union back in the 1990s are based on the standards of those days, which nowadays are still accessible and remain important research tools, e.g. NAVIS I-III (RGZM 2002; RGZM 2003). However, what was at that time considered as an extremely innovative project is nowadays experienced as a heavy burden to maintain. In the last few years, the 'classic SQL world' has been enhanced by newly developed open source RDBMS such as PostgreSQL and more specifically, with the geometry extension PostGIS.

Large industrial software and web application companies like Facebook and Google work nowadays with NoSQL storage solutions. The simple data model without the need of defining relations or structures allows for quick and efficient data management in distributed systems (Weber 2019; Meier and Kaufmann 2019). As a side effect, this storage technology is increasingly applied in several (archaeological) DH projects, which are based on NoSQL databases such as MongoDB or CouchDB (Lambers 2017).

Furthermore, a specific NoSQL data modelling in graphs is also becoming popular in archaeology. However, the hardest part is certainly the migration from existing authoritative large data repositories to make them available in formats that enable access to them from various analytical packages (Graham 2014: 43). Data is stored and used in classical graph databases like Neo4j. Also triplestores like RDF4J, Apache Jena Fuseki, Ontotext, Parliament and Virtuoso are now found in archaeology, such as the numismatic Nomisma project (Gruber 2013). Triplestores are based on the concept of the Semantic Web (W3C 2015) and Linked Data modelled using the Resource Description Framework (RDF) by RDF Working Group (2014) as well as the Web Ontology Language (OWL) by the OWL Working Group (2012) in a triple structure, following the rules of defining data according to subject - predicate - object.

Sharing and providing interoperable data as LOD is increasingly envisaged by archaeological institutions. Not only the RGZM, but also large research institutes like the Deutsches Archäologisches Institut, English Heritage and the Getty Research Institute are building web resources based on this kind of software architecture. However, it remains to be seen how popular these techniques will really become in archaeology or whether this

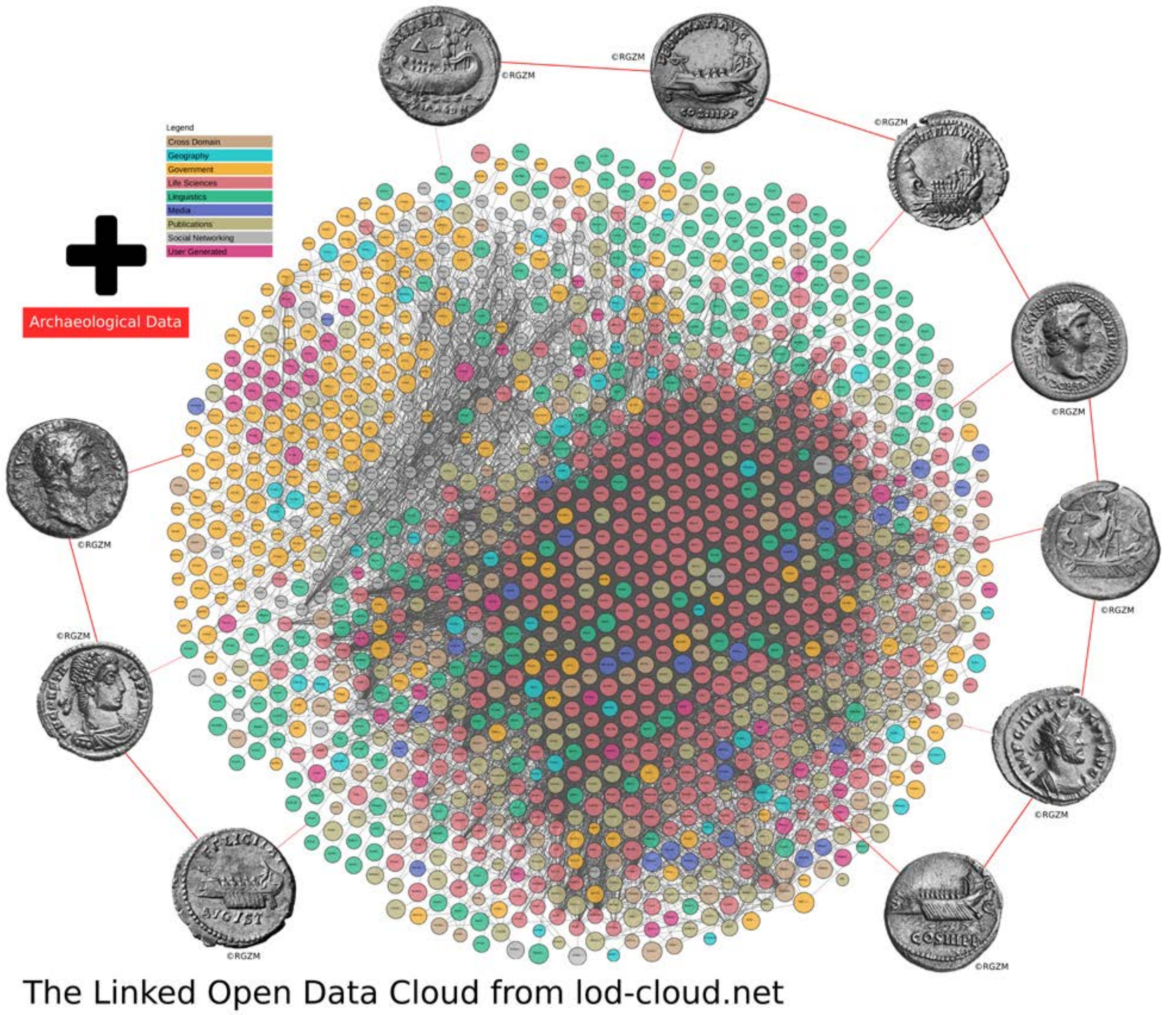

Figure 1. Archaeological LOD Cloud based on the LOD Cloud from lod-cloud.net (CC BY 4.0).

remains limited to the few who can afford the necessary resources. Stepping up these kinds of technologies also implies investing in considerably more advanced human IT resources, since archaeologists themselves are typically not able to handle these technologies themselves anymore. Therefore, it is important to balance the judgement as to whether these techniques should be applied or not. The grapes for graph databases are, by nature, hanging especially low in historical and archaeological branches where social relationships can be modelled with network analysis tools (Deicke 2017; Graham 2014). However, this also implies that there remain large research areas where these techniques do not really make sense - and generating knowledge here can be treated with rigid classical RDBMS methods, cf. chapter 4.1.

LOD in Archaeology

In 2011, Leif Isaksen described the application of Semantic Web technologies to the discipline of archaeology (Isaksen 2011) whilst constructing a foundation for further research in the field of ancient studies, including popular projects like 'Pelagios Commons'. On top of this, some well-known projects (e.g. Nomisma (Gruber and Lockyear 2015), Pelagios Commons (Simon et al. 2016) and PeriodO (Golden and Shaw 2016)) were established within the last few years, and an increasing number of researchers are getting involved. Following from that, the scientific LOD community is continuously growing. Researchers are linking datasets and resources from various sources to create an »Archaeological LOD Cloud« extension (cf. figure 1) as part of the 'Giant Global

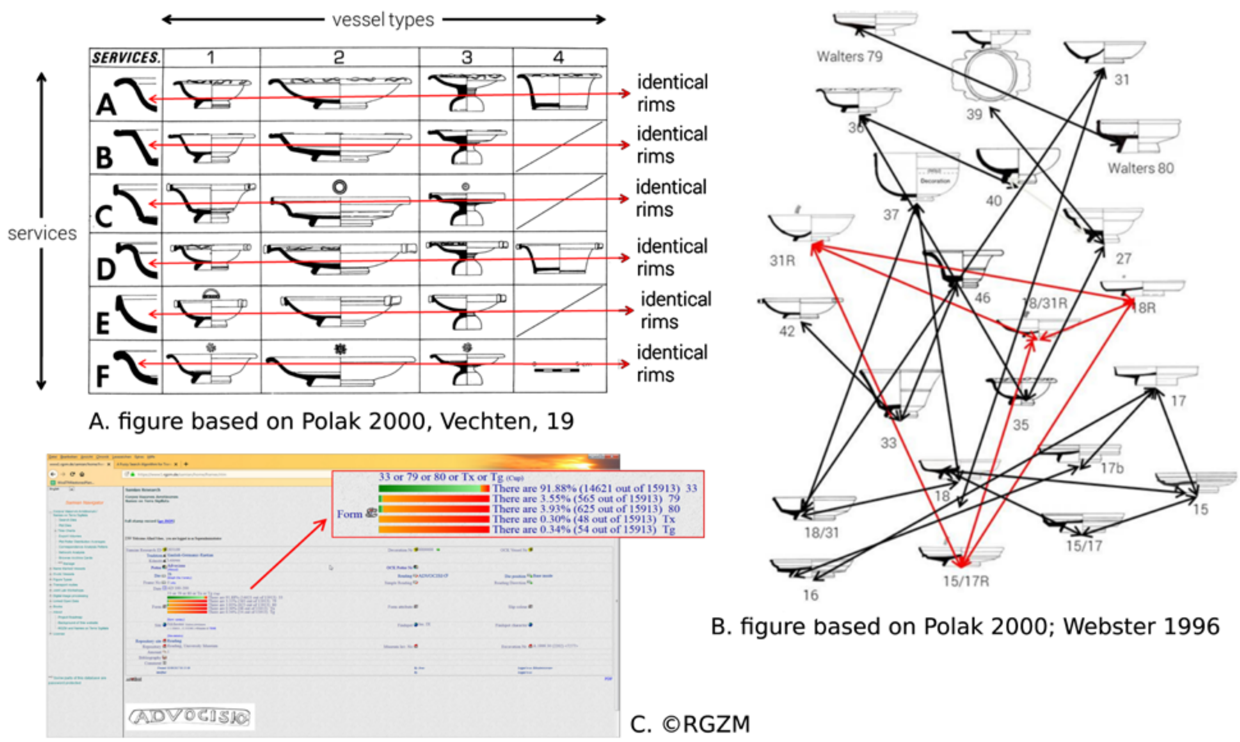

Figure 2. Historical 'service families' (A), archaeological form type attributions (B) and visualisation of degrees of vagueness in Samian Research (C).

Graph' (Berners-Lee 2007), or 'LOD Cloud' (McCrae 2018).

Modelling Doubts in Graphs

Theoretical work on uncertainty and imprecision and their relation to knowledge bases, has been carried out in the 1990s (Parsons 1996; Parsons 1998).

Following from that, Karsten Tolle and David Wigg-Wolf discussed a proposal for semantic modelling as LOD to describe uncertainties in the determination of coin representations (Tolle and Wigg-Wolf 2015). In particular, here the W3C Uncertainty Ontology (W3C-UN) has been used.

W3C-UN is based on the fact that a 'sentence' is subject to 'uncertainty', which has different characteristics: type, nature, derivation and the mathematical model (Laskey et al. 2008).

Moreover, statements or annotations without an exact degree of relation can be solved in the Semantic Web with the 'Open Annotation Ontology'. In this case, two web resources are linked together via a 'body' and a 'target' attribute (Sanderson, Ciccarese & Young 2017). The Pelagios Commons Initiative uses e.g. this ontology for linking data sets and resources of the gazetteer Pleiades (Muccigrosso 2018).

Efforts to enable working with the popular CIDOC CRM ontology (Niccolucci and Felicetti 2018) as a graph resulted in an extension of the CIDOC CRM enabling dealing with attributes of uncertainty (Bruhn et al. 2015).

Modelling Doubts in Thesauri: SKOS

The Simple Knowledge Organization System (Miles and Bechhofer 2009), short SKOS, is a formal language for encoding keywords in thesauri, using RDF and RDFS schema (Brickley and Guha 2014). SKOS offers semantic relations and mapping properties to express vague relationships between skos:Concepts. However, this raises the problem of transitivity and the general problem of 'fuzzy statements' about relations that cannot be quantitatively measured and evaluated:

> *"Note that skos:related is not a transitive property."* (Miles and Bechhofer 2009: #L2344)

> *"A skos:closeMatch link indicates that two concepts are sufficiently similar that they can be used*

Figure 3. Historical 'service families' (A), archaeological form type attributions (B) and visualisation of degrees of vagueness in Samian Research (C).

interchangeably in some information retrieval applications. A skos:exactMatch link indicates a high degree of confidence that two concepts can be used interchangeably across a wide range of information retrieval applications." (Miles and Bechhofer 2009: #L4858)

Uncertainty and Vagueness in Graphs

As demonstrated in section 2, modelling of doubts by using graphs is a challenge in archaeology. Since the perspective of interoperable and transparent research data for the scientific research community is so promising, it is worth the efforts. In this section, basic concepts and ideas for treating vagueness in graphs are introduced.

Uncertainty vs. Vagueness

There are two different types of doubts: 'uncertainty' and 'vagueness'. Vagueness can be seen as a statement which is not clearly formulated and allows room for individuals to draw their own conclusions. Uncertainty, however, is applicable when the correctness of a statement is not known, but can only be true or false.

Vagueness is a measure of the precision of a statement. A vague statement only applies to a certain extent. For example, if the weather report says »Tomorrow there will be rainfall« it could be a light drizzle, a moderate rain, or a heavy thunderstorm. A remedy could be, for example, the indication of the rainfall.

But a vague statement is not to be confused with an uncertain statement. Within uncertainty, it is completely unknown whether the statement is true at all. For example, if a weather report says, »Tomorrow there is a 75% chance of rain«, this is an uncertain statement. It indicates that in 3 out of 4 cases the message is true, so it rains tomorrow, and in 1 out of 4 cases it is wrong, so it does not rain tomorrow. In Dubois and Prade (2001) a more detailed clarification of the differences between vagueness and uncertainty is described.

In this paper, we only concentrate on vague statements and we assume that all vague statements can be expressed with values somewhere between 0 and 1. For example, a light rain with the value 0.25 (25%) could be used to say »Tomorrow there will be rainfall«. A heavy rain with the value 1.00 (100%) could

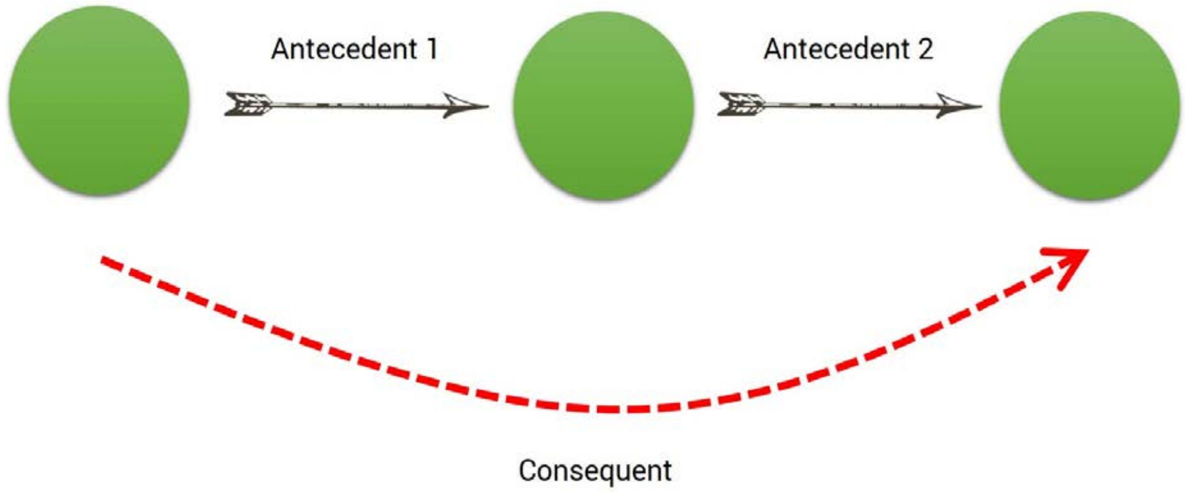

Figure 6. Schematic representation: Role-Chain-Axiom, green dots: concept instances, black arrows: role properties (antecedents), red arrow: inference (consequent).

be used to say »Tomorrow there will definitely be rainfall«

Vagueness in Graph-Based Data

Vagueness can theoretically occur in different places in a graph, but the range of vagueness in graph databases can be complex. The most common case is the assignment of a weight to a vague edge. This expresses to what degree or with what intensity the connection between the two nodes connected by the edge exists.

Analogously, it is also possible to provide additional information in a graph with a vague value. However, in this case we limit ourselves in our use of vagueness to the edge weight. In fact, in this paper, only values between 0 and 1 can be assigned a weighting. Such edge weights can be stored relatively easily in a decimal format in graph databases. More interesting is the actual processing of the edge weights by making rule-based conclusions, which means creating new edges that also carry vagueness.

Processing of the Edge Weights by Rule-based Conclusions

To process the edge weight by rule-based conclusions, techniques commonly utilised for description logics are used and applied to graph-based data as RDF. This has the advantage that the resulting graphs are directly connectable to other ontologies and LOD. A transformation of a vague description logic, interpreted in propositional logic, is realised through the use of multi-valued logic (Lukasiewicz and Straccia 2008). The disadvantage of multi-valued logic is that within them not all rules of classical propositional logic can apply, such as the 'law of De Morgan' or the 'double negation'. Although this disadvantage is persistent, various multi-valued logics can be used in combination.. This makes it possible to assign an individual interpretation to each rule.

Use Cases: Doubtful Statements in RDBMS and LOD

In this section, we describe ambiguous statements about Roman objects. All examples stem from work we did on this modelling issue during the last few years, available in online databases.

Use Case: Modelling Doubts in Samian Research

The Samian Research database comprises more than 245,000 stamped vessels on Roman Terra Sigillata (also called Samian). In antiquity, this pottery was highly standardised and in several cases even conceived as 'service families'. A 'service family' can e.g. consist of a cup, a dish and a bowl, having the same kind of rim or footring (Polak 2000). In modern times, archaeologists define different sub types

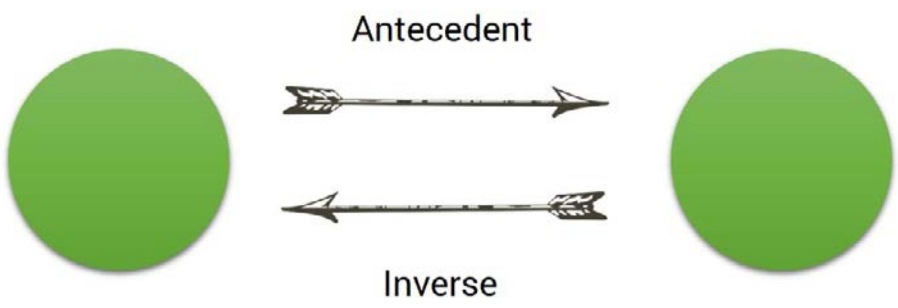

Figure 5. Schematic representation: Inverse-Axiom, green dots: concept instances, black arrows: role properties (antecedent / inverse)

(cf. figure 2B). Because the potters created e.g. identical rims across different pot forms, for modern archaeologists it is easy to identify a 'service family' if only the rim of a pot is preserved. But with only a rim or a footring in ones hand, the specific sub type can frequently not be identified (cf. red lines in figure 2A). Since archaeologists usually find broken parts of vessels (only a footring or only a rim), it is frequently not possible to attribute a pot fragment to one specific form type and usually there remains a (limited) range of form type possibilities (cf. red lines in figure 2B), resulting in vagueness within the typological attribution. Thus, trying to map pot fragments of Terra Sigillata to historically defined concepts of 'types' or 'service families' or even aligning these with typologies, frequently ends up in modelling doubtful assumptions. Typically, identical footrings occur on rouletted dishes of different pot form types (cf. red lines in figure 2B). The Samian online research community uses abstract 'OR' strings in the RDBMS world to model this vagueness. Such an 'OR' statement on its own is not particularly meaningful, but a function within the SQL database querying routine can provide statistical metrics and to specify the degrees of vagueness of the possible form type attributions involved. A simple visualisation of the vagueness degree in coloured bars, indicating the statistical likelihood of the possible pot form attributions, is easily interpretable for the scientific community (cf. figure 2C) (RGZM 2018).

Use Case: Modelling Doubts in the NAVIS Ship Databases

The NAVIS ship databases I, II and III are comprised of thousands of images that show Roman ancient shipwrecks, ship depictions on ancient monuments and coins to be described using SKOS.

Use Case: is it Nero?

A Roman coin with the head of Nero within the NAVIS III database can be described by using a LOD resource (e.g. Nomisma.org (2017)). The question »Is it Nero?« can easily be answered by using skos:exactMatch =100% Nero (cf. figure 3A).

Use Case: Sailed or Rowed?

Another example from NAVIS III can be used for describing the propulsion of a ship on a coin. In this ship depiction (cf. figure 3B), there is vagueness involved. It is not clear whether this kind of ship was sailed or rowed, since there are also fresco depictions where this ship type is displayed in a sailing mode. Therefore, we could describe the situation by using skos:relatedMatch ≥50% sailed ≥50% rowed (cf. figure 3B-C).

Use Case: Lateen Sail or Foresail?

A more difficult example (cf. figure 3D) from the NAVIS II database deals with the 'sailing gear' on a relief. The triangular sail in front of the scene can be described as a triangular lateen sail being used as a 'foresail', a very unlikely scenario. Hence the idea that it could actually be a squared foresail that is being hoisted, this being the more likely scenario because of the adjacent person. It is important to distinguish between the sail types, because there are completely different functions attached to them. From the contextual evidence, this can be solved as follows: skos:relatedMatch ≥1% 'lateen sail' ≥99%' fore sail'.

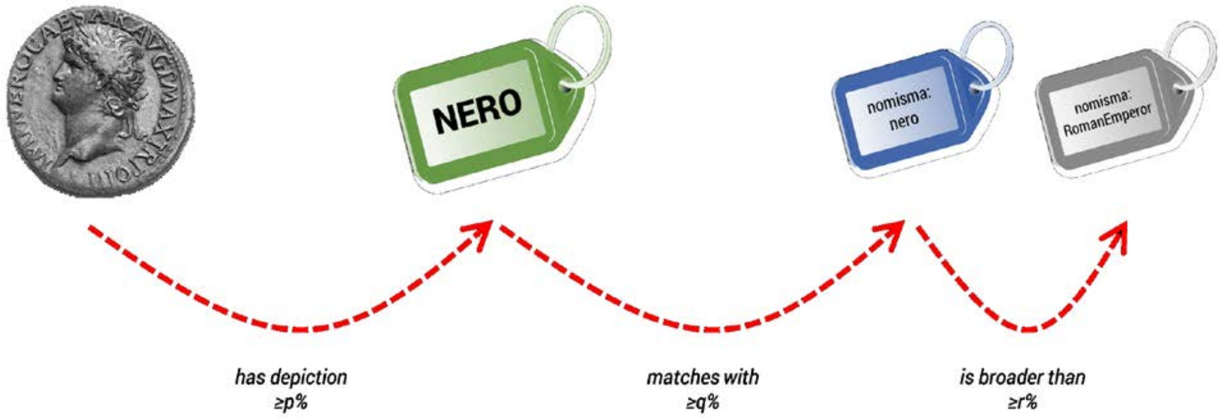

Figure 6. Schematic representation: NAVIS ontology connections.

Use Case: Transport Vessel or Military Vessel?

A further example from NAVIS II (cf. figure 3E) describes the ship function on the so called 'Neumagen relief'. This is an example of vagueness: the ship could have been either used for warfare (the ship type is known on coin depictions with military contexts only) or trade (looking at the loaded wine barrels). Therefore, the available options are: transport vessel or military vessel, in which case we use skos:relatedMatch ≥40% 'transport vessel' ≥60% 'military vessel'.

Use Case: Linking a Triangular Lateen Sail to the LOD Cloud

When trying to link a triangular 'lateen sail' from the NAVIS II database (cf. figure 3F) into the LOD Cloud, it is revealing that each external repository has completely different 'hidden assumptions' in its hierarchies that are related to its specific scientific domain. The internal organisation of the Getty AAT thesaurus or the FISH Maritime Craft Types Thesaurus resources, follow entirely different principles and a correct entry level may be missing. SKOS based relations cannot solve this challenge to model the degree of doubt involved. In such cases, a different approach is required to cope with the hierarchical 'hidden assumptions' implied in these thesauri. As a generic rule, in such cases we can only link a 'lateen sail' to Getty AAT or FISH Maritime Craft Types Thesaurus by skos:relatedMatch ≥p% sails (equipment) ≥q% 'CORVETTE SAIL'.

Academic Meta Tool

Since there is no tool available to our needs in order to model vagueness and ambiguity in combination with reasoning using LOD techniques, we implemented it ourselves. AMT provides web based functions for modelling doubts as LOD including reasoning. It is developed by Martin Unold and Florian Thiery from the Mainz Center for Digitality in the Humanities and Cultural Studies (mainzed), the Institute for Spatial Information and Surveying Technology (i3mainz) and the RGZM (Thiery and Unold 2018a).

AMT Meta Ontology

When using AMT, it is necessary to develop an ontology (Thiery and Unold 2018b; Thiery and Unold 2018c). This ontology describes the schema and axioms for a particular application scenario. In the ontology four types of statements are available.

For demonstrating the individual types of statements we are using an example ontology to model locations that face each other in different directions. To compare the AMT ontology with OWL, we align it with corresponding expressions in the Web Ontology Language (Hitzler et al. 2012).

First of all, it is possible to specify categories for nodes. We also call such categories 'Concepts'. This corresponds to the predicate owl:Class. Each concept can be assigned a name and a short description. For example, the concept of a 'Place' as a point or an area on Earth's surface can be assigned to a place instance

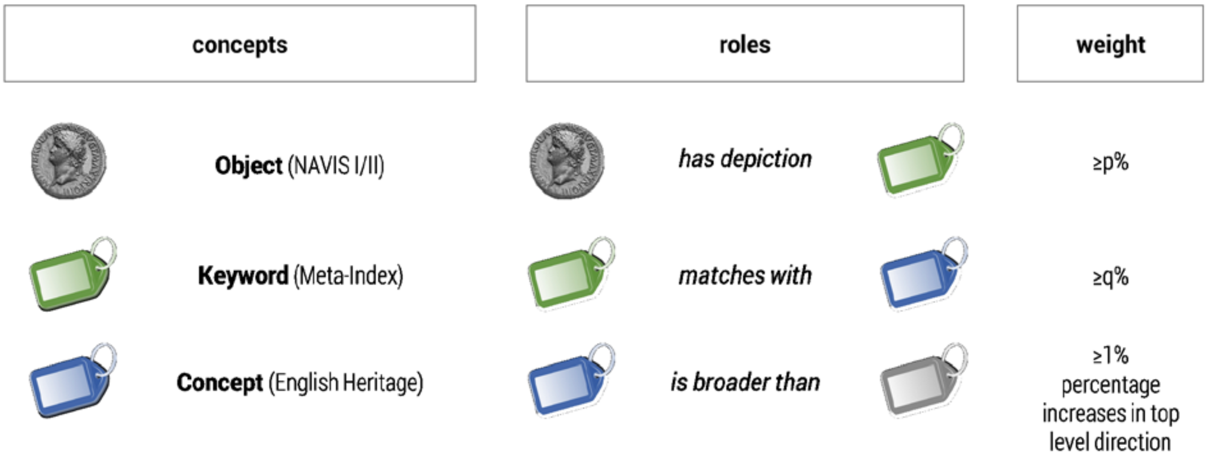

Figure 7. Schematic representation: NAVIS ontology concepts and roles.

'Budapest' in its location at 120 AD, which has a different location compared to the medieval or modern 'Budapest'.

Analogously, categories for edges can also be specified. We call these Roles. This corresponds to the predicate owl:ObjectProperty. Each role can be assigned a name and a concept for source nodes (=rdfs:domain) and destination nodes (=rdfs:range). Example: the roles 'northOf', 'eastOf', 'southOf' and 'westOf' which have a 'Place' as a source and a destination node.

In addition, two types of axioms can be formulated. One type is the role-chain-rule (cf. figure 4). It roughly corresponds to owl:ObjectPropertyChain. However, in addition to specify the roles in the chain, AMT must directly declare the resulting role. Moreover, it must also be determined according to which multivalued logic (e.g. Goedel) the reasoning should take place.

The other type of axiom is the inverse (cf. figure 5). It corresponds to owl:inverseOf. Here you have to specify the role and its inverse. Example: 'northOf' is the inverse of 'southOf'.

AMT JavaScript Library

For web implementation of use cases, a JavaScript library can be used (Unold and Thiery 2018). The amt.js library provides data management functionality, communication with a database server (here: RDF4J triplestore) and a reasoning program. However, each example ontology requires the implementation of an individual web viewer to display and edit the data.

AMT Example of the NAVIS Ship Databases

The aim of this paper is to demonstrate a proposal related to defining keywords for subject indexing depictions of several items within the NAVIS ship databases in the central-index of the RGZM, aligning them to authoritative thesauri to obtain additional information like the hierarchical information (cf. figure 6).

One attempt to find a solution for semantic modelling of uncertainty using Linked Data was done by Tolle and Wigg-Wolf (2015) when dealing with ancient coinage: On a Roman coin, a portrait of a person is shown. Important for further usage is the clear identification of the person. In a survey of experts a 100% certainty could not be ensured: »I am 80% sure that the portrayed person is Titus, or the likelihood is 60% Titus and 40% Nero« (Tolle and Wigg-Wolf 2015: 173). This result was achieved by letting the scholars identify the person according to their own standards without permitting them to indicate likelihood. Only in the post processing the statistical distribution of the identifications was used to indicate the likelihood of the identification.

A similar problem arises in the NAVIS ship databases of the RGZM. In NAVIS II, depictions of ships on mosaics, monuments, etc. are made available on the Web (RGZM 2002); in NAVIS III, ship representations on coins are made available to the scientific community (RGZM 2003). In both databases, analogous to the case of Tolle and Wigg-Wolf, the representations are assigned to an attribute, e.g.

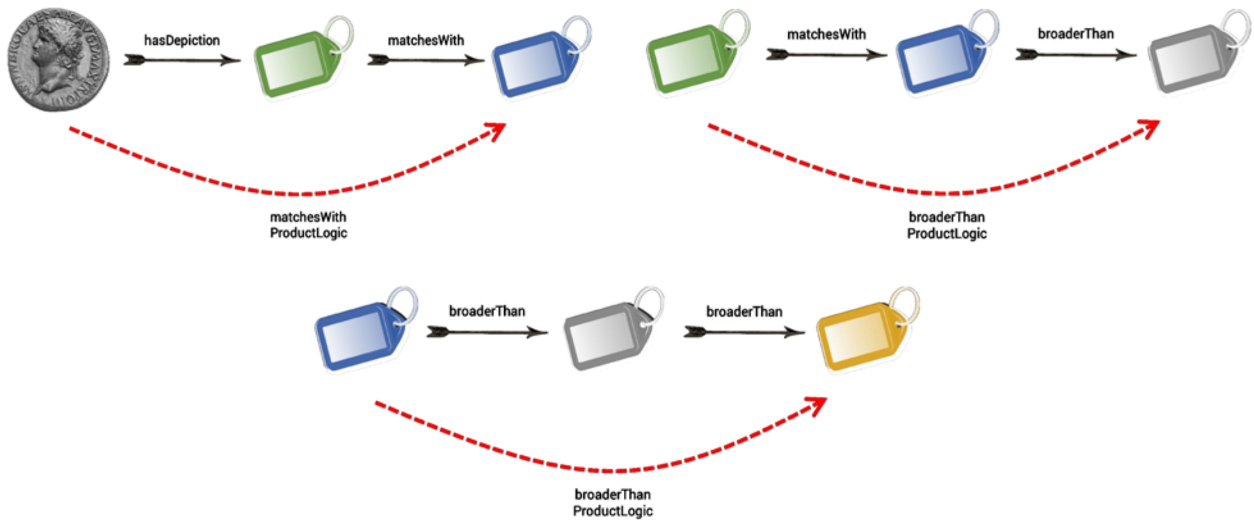

Figure 8. Schematic representation: NAVIS ontology axioms.

Titus and Nero, but also trade and war or paddled and rowed. So far, these links are modelled 1:1 with a 100% possible security in the data model. In order to give objectivity to this very subjective perception, a vague connection that exists only to a certain degree would be transparent and comprehensible. In addition, keywords of object representations are aligned to LOD thesauri concepts. In these thesauri, however, there are again dependencies to a certain degree, which cannot be mapped exactly by means of the used SKOS ontology. However, this is necessary for the content development. Using AMT is a way to semantically model the process from looking at the object for keyword tagging to linking to a thesaurus concept.

AMT NAVIS Ontology

For this use case, a small AMT NAVIS ontology must be implemented. It consists of three concepts, six roles and 18 axioms (Thiery and Mees 2018b).

The NAVIS ontology contains the concepts Object (O), Keyword (K) and Concept (C). The roles (O)-[hasDepiction]->(K) and (K)-[isDepictionOf]->(O) are used to link the object to the keyword. For the connection between keyword and thesaurus concept there are the roles (K)-[matchesWith]->(C) and (C)-[matchedBy]->(K), as well as for the hierarchical order in the thesaurus the roles (C)-[broaderThan->(C) and (C)-[narrowerThan]->(C). Here we assume that the degree of linkage increases the further it goes in the direction of the top-level concept, the degree of the other links must be determined by the scientist himself. Figure 7 shows the concepts and roles.

Three role-chain-rules (including the respective inverse) with suitable logics are introduced (see figure 8): These are:

* Axiom01: (A)-[hasDepiction]->(B)-[matchesWith]->(C) => (A)-[matchesWith;ProductLogic]->(C)
* Axiom02: (A)-[matchesWith]->(B)-[broaderThan]->(C) => (A)-[broaderThan ;ProductLogic]->(C)
* Axiom03: (A)-[broaderThan]->(B)-[broaderThan]->(C) => (A)-[broaderThan ;ProductLogic]->(C)

In addition, six inverse axioms and six disjoint axioms are added.

The role-chain-rules in the NAVIS ontology lead to the following conclusions: If an object is tagged with a keyword and linked to a concept in a thesaurus, there is also a certain degree of connection between the object and the thesaurus concept, cf. Axiom01. If this thesaurus concept is a broader concept in the thesaurus, the keyword is also linked to it with a certain degree, cf. Axiom02. In addition, all hierarchically organized keywords in the thesauri have relationships to some degree, cf. Axiom03.

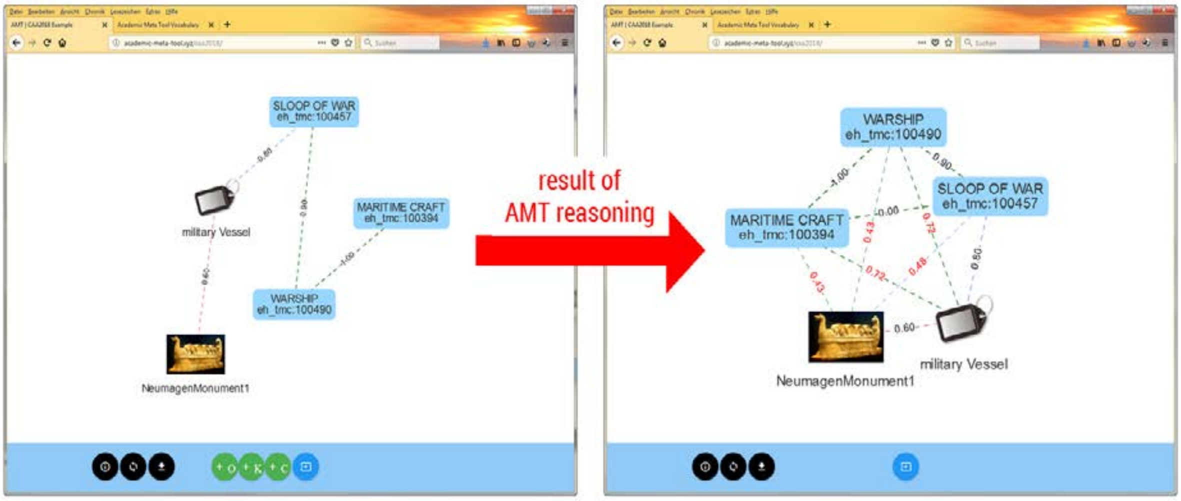

Figure 9. NAVIS ontology reasoning example in the web viewer.

Figure 10: Schematic representation: Inverse-Axiom, green dots: concept instances, black arrows: role properties (antecedent / inverse)

We can demonstrate this in two examples from the NAVIS II ship databases: a depiction shows a ship: Is it a rudder or a sailing ship? Here the scientist can decide for ≥50% sailing ship or ≥50% rowing ship. Another illustration shows a relief. The ship depicted on it could represent a transport or a military ship, since both wine barrels and soldiers can be seen. Again, the scientist can now decide, probably ≥40% transport ship or ≥60% military vessel, cf. figure 3, image B and D.

Example Reasoning in the Web Viewer

AMT reasoning can be visualised on the web (Thiery, Mees & Unold 2018). The visualisation is based on the existing vis.js framework (visjs 2019). This package allows for web based, low-threshold usability. The reasoning implementation is available in a specific amt.js library (cf. section 5.2).

Figure 9 illustrates an example of the question »Is it a military vessel or not?«. On the left, the input graph is visualized. In our example the 'Neumagen Monument 1' Object is connected with a degree of 60% to the 'military vessel' keyword. This keyword matches with 80% to the 'SLOOP OF WAR' item (eh_tmc:100457) in the 'FISH Maritime Craft Types Thesaurus', short eh_tmc (English Heritage 2013). In this thesaurus a hierarchical structure is modelled (FISH 2018b): the thesaurus concept of 'sloop of war' has a broader concept 'WARSHIP' (eh_tmc:100490) and this concept is attached to the top level item 'MARITIME CRAFT' (eh_tmc:100394). As described in chapter 6.1 the degree of linkage increases in the direction of the top-level concept. So here we modelled (eh_tmc:100457) -[90%]-> (eh_tmc:100490) -[100%]-> (eh_tmc:100394). After AMT reasoning, new conclusions can be drawn, cf. figure 9, right side (red numbers): The monument is connected with a degree of 48% to 'SLOOP OF WAR', 43% to 'WARSHIP' and 43% to 'maritime craft'. Our keyword 'military vessel' is connected with a degree of 72% to 'WASHIP' and 72% to 'MARITIME CRAFT'.

The resulting knowledge graphs can be downloaded in different formats (e.g. RDF, JSON, CSV or cypher) for further usage, cf. figure 10.

Outlook

In the last sections we demonstrated that modelling doubts in archaeological research by using an ontology from AMT can help to tame the ambiguities in LOD. However, there still remain challenges and work that will have to be done in the future:

1. Rules in AMT are currently limited, cf. chapter 5. There are ideas of the AMT developers to add more rules in newer versions of AMT. However, AMT rules cannot be extended to the expressive power of OWL because of limitations in the handling of contradictions.

2. The role-chain-rule, even without considering the vagueness, is supported by only a few reasoners, e.g. Straccia (2015), Bobillo and Straccia (2008), Bobillo and Straccia (2011), Tsatsou et al. (2014) but not yet for LOD purposes.

3. Using web standards such as RDF and OWL makes it easy to connect the AMT reasoned data directly to other LOD. Thus, information created with AMT can be linked to other resources and contribute to the enrichment of the Giant Global Graph. Unfortunately, the modelling of vagueness in the Semantic Web is not yet standardized by the World Wide Web Consortium (W3C). Therefore, for the moment there is no way around using an in-house development such as AMT to model vagueness in LOD.

4. As discussed in chapter 3, the AMT ontology only supports vagueness and not uncertainty. The software is therefore suitable for modelling humanities research questions, in which a lot of knowledge is considered as secured, but not all. A classical modelling (without vagueness) fails because of decent categorisation, examples discussed in chapter 6. By using AMT, data modelling is not based on binary decisions (yes or no), but based on decisions that are only valid to a certain degree.

5. The current JavaScript library will be enhanced by a full server based Java library using Apache Jena which will be made freely available to the scientific community.

NAVIS database Update

After finishing the manuscript, the NAVIS I-III databases have been updated and merged into one unified platform using a single CIDOC CRM based data model, called NAVIS (LEIZA 2023: Thiery and Mees 2023a). The thesauri, which were dispersed between NAVIS I, II and III, have been unified and are now available as SKOS based resources 'Maritime Thesaurus' (Thiery and Mees 2023b; Thiery and Mees 2023c).

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The example data is published under a CC BY 4.0 licence in the research data repository Zenodo (Thiery and Mees 2018a). The source code of the web viewer prototype is published under a MIT licence (Thiery 2018).

References

Beagrie, N 1993 The Computerisation of the National Archaeological Record, *Revue Informatique et Statistique dans les Sciences Humaines*, 29(1): 9–16.

Berners-Lee, T 2006 Linked Data. 27 July 2006. Available at https://www.w3.org/DesignIssues/LinkedData.html [Last accessed 14 August 2018].

Berners-Lee, T 2007 Giant Global Graph. 21 November 2007. Available at https://web.archive.org/web/20170629153546/http://dig.csail.mit.edu:80/breadcrumbs/node/215 [Last accessed 14 August 2018].

Bobillo, F and Straccia, U 2008 fuzzyDL: An expressive fuzzy description logic reasoner. *2008 IEEE International Conference on Fuzzy Systems (IEEE World Congress on Computational Intelligence)*. June 2008 Hong Kong, China: IEEE, pp. 923–930. DOI: https://doi.org/10.1109/FUZZY.2008.4630480.

Bobillo, F and Straccia, U 2011 Fuzzy ontology representation using OWL 2, *International Journal of Approximate Reasoning*, 52(7): 1073–1094. DOI: https://doi.org/10.1016/j.ijar.2011.05.003.

Brickley, D and Guha, R V 2014 *RDF Schema 1.1.* 25 February 2014. Available at https://www.w3.org/TR/rdf-schema/ [Last accessed 14 August 2018].

Bruhn, K-C, Engel, T, Kohr, T and Gronenborn, D 2015 Integrating Complex Archaeological Datasets from the Neolithic in a Web-Based GIS. In: Giligny, F., Djindjian, F., Costa, L., Moscati, P., and Robert, S. (eds.) *CAA2014. 21st Century Archaeology. Concepts, methods and tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*. Oxford: Archaeopress, pp. 341–348.

Deicke, A 2017 Networks of Conflict: Analyzing the 'Culture of Controversy' of Polemical Pamphlets of Intra-Protestant Disputes (1548-1580), *Journal of Historical Network Research*, 71-105 Pages. DOI: https://doi.org/10.25517/jhnr.v1i1.8.

Dubois, D and Prade, H 2001 Possibility theory, probability theory and multiple-valued logics: A clarification. *Annals of mathematics and Artificial Intelligence*, 32(1-4): 35–66.

English Heritage 2013 *MARITIME CRAFT TYPE (EH).* 17 July 2013. Available at http://purl.org/heritagedata/schemes/eh_tmc [Last accessed 14 August 2018].

Forum on Information Standards in Heritage 2018a *FISH TERMINOLOGIES. Archaeological Science Thesaurus.* January 2018. Available at http://www.heritage-standards.org.uk/wp-content/uploads/2018/02/ArchSci_alpha.pdf [Last accessed 14 August 2018].

Forum on Information Standards in Heritage 2018b *FISH TERMINOLOGIES. Maritime Craft Type Thesaurus.* January 2018. Available at http://www.heritage-standards.org.uk/wp-content/uploads/2018/02/MarCraft_alpha.pdf [Last accessed 14 August 2018].

Golden, P and Shaw, R 2016 Nanopublication beyond the sciences: the PeriodO period gazetteer, *PeerJ Computer Science*, 2: e44. DOI: https://doi.org/10.7717/peerj-cs.44.

Graham, S 2014 On Connecting Stamps - Network Analysis and Epigraphy. *Les Nouvelles de l'archéologie*, 135(3): 39–44.

Gruber, E 2013 *Nomisma: Using XForms to Manage and Publish Linked Open Data.* 18 July 2013. Available at http://numishare.blogspot.com/2013/07/nomisma-using-xforms-to-manage-and.html [Last accessed 14 August 2018].

Gruber, E and Lockyear, K 2015 From dBase III+ to the Semantic Web: Twenty Five Years of the Coin Hoards of the Roman Republic Database. In: Traviglia, A. (ed.) *Across Space and Time. Papers from the 41st Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*. 2015 Amsterdam: Amsterdam University Press, pp. 336–346.

Heritage Data 2013 *Heritage Data Vocabularies.* Available at http://www.heritagedata.org/blog/vocabularies-provided/ [Last accessed 14 August 2018].

Hitzler, P, Krötzsch, M, Parsia, B, Patel-Schneider, P F and Rudolph, S 2012 *OWL 2 Web Ontology Language Primer* (Second Edition). 11 December 2012. Available at http://www.w3.org/TR/2012/REC-owl2-primer-20121211/ [Last accessed 14 August 2018].

Isaksen, L 2011 *Archaeology and the Semantic Web*. Thesis (Doctoral). University of Southampton.

J. Paul Getty Trust 2017 *Art & Architecture Thesaurus® Online*. 7 March 2017. Available at http://www.getty.edu/research/tools/vocabularies/aat/ [Last accessed 14 August 2018].

Lambers, R 2017 *NoSQL databases in Archaeology, a Funerary Case Study.* Thesis (MSc) Digital Archaeology, Universiteit Leiden.

Laskey, K J, Laskey, K B, Costa, P C G, Kokar, M, Martin, T and Lukasiewicz, T 2008 *Uncertainty Reasoning for the World Wide Web.* 31 March 2008. Available at https://www.w3.org/2005/Incubator/urw3/XGR-urw3-20080331/ [Last accessed 14 August 2018].

Leiza 2023 *NAVISone Ship Database.* Available at https://www.leiza.de/navis [Last accessed 20 March 2023]

Lukasiewicz, T and Straccia, U 2008 Managing uncertainty and vagueness in description logics for the Semantic Web. *Web Semantics: Science, Services and Agents on the World Wide Web*, 6(4): 291–308. DOI: https://doi.org/10.1016/j.websem.2008.04.001.

McCrae, J P 2018 *The Linked Open Data Cloud.* Available at https://lod-cloud.net/ [Last accessed 14 August 2018].

Meier, A and Kaufmann, M 2019 NoSQL Databases. In: *SQL & NoSQL Databases*. Wiesbaden: Springer Fachmedien Wiesbaden. pp. 201–218. DOI: https://doi.org/10.1007/978-3-658-24549-8_7.

Miles, A and Bechhofer, S 2009 *SKOS Simple Knowledge Organization System Reference.* 18 August 2009. Available at https://www.w3.org/TR/2009/REC-skos-reference-20090818/ [Last accessed 14 August 2018].

Niccolucci, F and Felicetti, A 2018 A CIDOC CRM-based Model for the Documentation of Heritage Sciences. *2018 3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)*. October 2018 San Francisco, CA, USA: IEEE. pp. 1–6. DOI: https://doi.org/10.1109/DigitalHeritage.2018.8810109.

Muccigrosso, J 2018 *Joining Pelagios.* 22 June 2018. Available at https://github.com/pelagios/pelagios-cookbook/wiki/Joining-Pelagios [Last accessed 14 August 2018].

Nomisma.org 2017 nero (foaf:Person). 28 April 2017. Available at http://nomisma.org/id/nero [Last accessed 14 August 2018].

OWL Working Group 2012 *Web Ontology Language (OWL).* 11 December 2012. Available at https://www.w3.org/OWL/ [Last accessed 14 August 2018].

Parsons, S 1996 Current approaches to handling imperfect information in data and knowledge bases, *IEEE Transactions on Knowledge and Data Engineering*, 8(3): 353–372. DOI: https://doi.org/10.1109/69.506705.

Parsons, S 1998 Addendum to 'Current approaches to handling imperfect information in data and knowledge bases', *IEEE Transactions on Knowledge and Data Engineering*, 10(5): 862.

Polak, M 2000 *South Gaulish Terra Sigillata with Potters' Stamps from Vechten*. Rei Cretariae Romanae Fautorum Acta, Supplementum 9. Nijmegen: Katholieke Universiteit Nijmegen.

RDF Working Group 2014 *Resource Description Framework (RDF).* 25 February 2014. Available at https://www.w3.org/RDF/ [Last accessed 14 August 2018].

RGZM 2002 *The NAVIS II project.* Available at http://www.rgzm.de/navis2 [Last accessed 14 August 2018].

RGZM 2003 NAVIS III. *Römische Schiffsmünzen im RGZM.* Available at http://www.rgzm.de/navis3 [Last accessed 14 August 2018].

RGZM 2018 *Samian research.* Available at http://rgzm.de/samian [Last accessed 14 August 2018].

Sanderson, R, Ciccarese, P and Young, B 2017 *Web Annotation Data Model.* 23 February 2017. Available at https://www.w3.org/TR/2017/REC-annotation-model-20170223/ [Last accessed 14 August 2018].

Simon, R, Isaksen, L, Barker, E and de Soto Cañamares, P 2016 The Pleiades Gazetteer and the Pelagios Project. In: Berman, M L, Mostern, R, and Southall, H (eds.) *Placing names: enriching and integrating gaz-*

etteers. The spatial humanities. Bloomington: Indiana University Press. pp. 97–109.

Straccia, U 2015 The fuzzyDL System. Available at http://www.umbertostraccia.it/cs/software/fuzzyDL/fuzzyDL.html [Last accessed 14 August 2018].

Thiery, F 2018 *Academic Meta Tool - NAVIS example web app (CAA2018)*. DOI: https://doi.org/10.5281/zenodo.1344297.

Thiery, F and Mees, A 2018a *Academic Meta Tool - NAVIS example data (CAA2018)*. DOI: https://doi.org/10.5281/zenodo.1344295.

Thiery, F and Mees, A 2018b *Academic Meta Tool - Navis Ontology.* DOI: https://doi.org/10.5281/zenodo.1341111.

Thiery, F, Mees, A and Unold, M 2018 *AMT. Academic Meta Tool. CAA 2018 Example.* Available at http://academic-meta-tool.xyz/caa2018/ [Last accessed 14 August 2018].

Thiery, F and Mees, A 2023a NAVIS.one: Challenges and Opportunities for RSE and RDM by designing a common web application from a 1990s online database, *Squirrel Papers* 2022, (4)3, No. 15. DOI: https://doi.org/10.5281/zenodo.7142170.

Thiery, F and Mees, A 2023b NAVISone Maritime Thesaurus, *Squirrel Papers* 2022, (4)2, No.4. DOI: https//doi.org/10.5281/zenodo.7353771.

Thiery, F and Mees, A 2023c *NAVISone Maritime Thesaurus* [GitHub archaeolink]. Available at https://github.com/archaeolink/navisone-maritime-thesaurus/blob/main/data/navisone_maritime_thesaurus.ttl [Last accessed 20 March 2023]

Thiery, F and Unold, M 2018a *Academic Meta Tool – Ein Web-Tool zur Modellierung des Zweifels.* DOI: https://doi.org/10.5281/zenodo.1155727.

Thiery, F and Unold, M 2018b *Academic Meta Tool – Ontology.* DOI: https://doi.org/10.5281/zenodo.1342536.

Thiery, F and Unold, M 2018c *Academic Meta Tool - Vocabulary.* DOI: https://doi.org/10.5281/zenodo.1342530.

Tolle, K and Wigg-Wolf, D 2015 Uncertainty Handling for Ancient Coinage. In: Giligny, F., Djindjian, F., Costa, L., Moscati, P., and Robert, S. (eds.) *CAA2014. 21st Century Archaeology. Concepts, methods and tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* 2015 Oxford: Archaeopress, pp. 171–178.

Tsatsou, D, Dasiopoulou, S, Kompatsiaris, I and Mezaris, V 2014 LiFR: A Lightweight Fuzzy DL Reasoner. In: *The Semantic Web: ESWC 2014 Satellite Events. Lecture Notes in Computer Science.* 25 May 2014 Springer, Cham. pp. 263–267. DOI: https://doi.org/10.1007/978-3-319-11955-7_32.

Unold, M, Cruz, C, Boochs, F and Bruhn, K-C 2017 *Basic types of non-boolean description logics.* Available at http://unold.net/research/p_dls_20170320.pdf [Last accessed 14 August 2018].

Unold, M and Cruz, C 2017 How to enrich description logics with fuzziness. In: *2017 Computing Conference.* July 2017 London: IEEE. pp. 51–57. DOI: https://doi.org/10.1109/SAI.2017.8252080.

Unold, M and Thiery, F 2018 *Academic Meta Tool - amt.js.* DOI: https://doi.org/10.5281/zenodo.1342310.

visjs 2019 Network. Available at https://visjs.github.io/vis-network/docs/network/ [Last accessed 20 September 2019].

W3C 2015 *SEMANTIC WEB.* Available at https://www.w3.org/standards/semanticweb/ [Last accessed 14 August 2018].

Weber, S 2019 *NoSQL Databases.* Available at https://wiki.hsr.ch/Datenbanken/files/Weber_NoSQL_Paper.pdf [Last accessed 10 September 2019].

Webster, P 1996 *Roman samian pottery in Britain*. C.B.A. Practical Handbook in Archaeology 13. New York.

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Adam Pažout
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Evaluating QField as a Mobile GIS Solution for Archaeological Survey

Adam Pažout
Zinman Institute of Archaeology
University of Haifa
a.pazout@seznam.cz

Abstract

The recent developments in the field of geospatial 'free and open source software' (F/OSS) are reflected in its more widespread use among archaeologist. The article presents practical application of one of these F/OSS programs, namely QField, for archaeologists. QField is mobile version of desktop GIS program QGIS, customized for Android platform. The salvage survey in the northern Israel at the site of Khirbet es-Swade/Ma'agar Snir and survey of Hellenistic and Roman fortifications in the southern Golan Heights provide case-studies for the utilization of the program. The program's performance is evaluated with regard to 1) preparation and pre-processing of the data; 2) data collection and fieldwork; and 3) data export and post-processing.

Keywords: Archaeological survey; Archaeological methods; Mobile GIS; Open source software; Israel

Introduction

The use of various computer applications in archaeology for recording, storage and analysis of the data is common occurrence in the contemporary research which encompasses survey, excavations and post-fieldwork analysis (Tripcevich – Wernke 2010; Orengo 2015; Averett – Gordon – Counts eds. 2016 which contains overview of recent developments). While in past many archaeologists, as other professionals, depended on proprietary (also 'closed source') software, nowadays more scholars are turning to 'free and open source software' (F/OSS). Only F/OSS, is claimed (Ducke 2012; 2015), can provide researchers with control over data processing and allows reproducibility of the research, due to its open source code. Moreover, since most F/OSS programs are free of charge under liberal open source licenses (such as GNU General Public License) they can be easily incorporated even into long-term research project or used for education purposes with little to no cost.

Therefore, it was decided to use F/OSS program in order to evaluate its possibilities and potential for archaeological survey and its performance during the fieldwork on two case studies. The first to be presented is initial salvage survey of the site Khirbet es-Swade/ Ma'agar Snir in northern Israel and the second one is the survey of Hellenistic and Roman fortifications in the southern Golan Heights (Fig. 1). The program in question is QField and it was chosen for three reasons: 1) it is F/OSS and free of charge; 2) it works offline and 3) it is built on QGIS which is another F/OSS desktop GIS (Geographic Information System) program that is already used by number of professionals, including archaeologists. The basic functions of the program and the workflow, from the survey design through project setup to post-survey work will be described. The program's performance will be evaluated with regard to 1) preparation and pre-processing of the data; 2) data collection and fieldwork; and 3) data export and post-processing (Wagtendonk – De Jeu 2007). This paper should serve as a brief guide through one out of several existing programs for scholars interested in (or who are already using) digital solutions in the fieldwork.

Figure 1. Study region of the two case studies..

Software and Hardware

QField is in fact light version of desktop program QGIS (formerly QuantumGIS) customized for Android platform (version 4.3 and later) so that it can be used off-line on portable devices in the field. The developers emphasize QField is the QGIS since it is based on same source code. The program was built around three ideas: be compatible with QGIS, keep it as simple as possible and that it is mode-based.

The workflow begins with creation of portable project on desktop QGIS which will be uploaded onto the Android device. That means that in the first step user prepares all data he/she will need in the field in QGIS, including setting coordinate system and project and layer properties (such as display, read-only and identify behaviour etc.). The compatibility of the two programs allows for all settings made in QGIS to work also in QField. The project is saved in QGIS project format (.qgs), which is stored together with the rest of the project data (layers etc.) in a single directory that is uploaded into the portable device. The configuration of the portable project itself into the project directory can be made either manually or using QFieldSync plugin for QGIS which can also serve for synchronizing collected data from portable

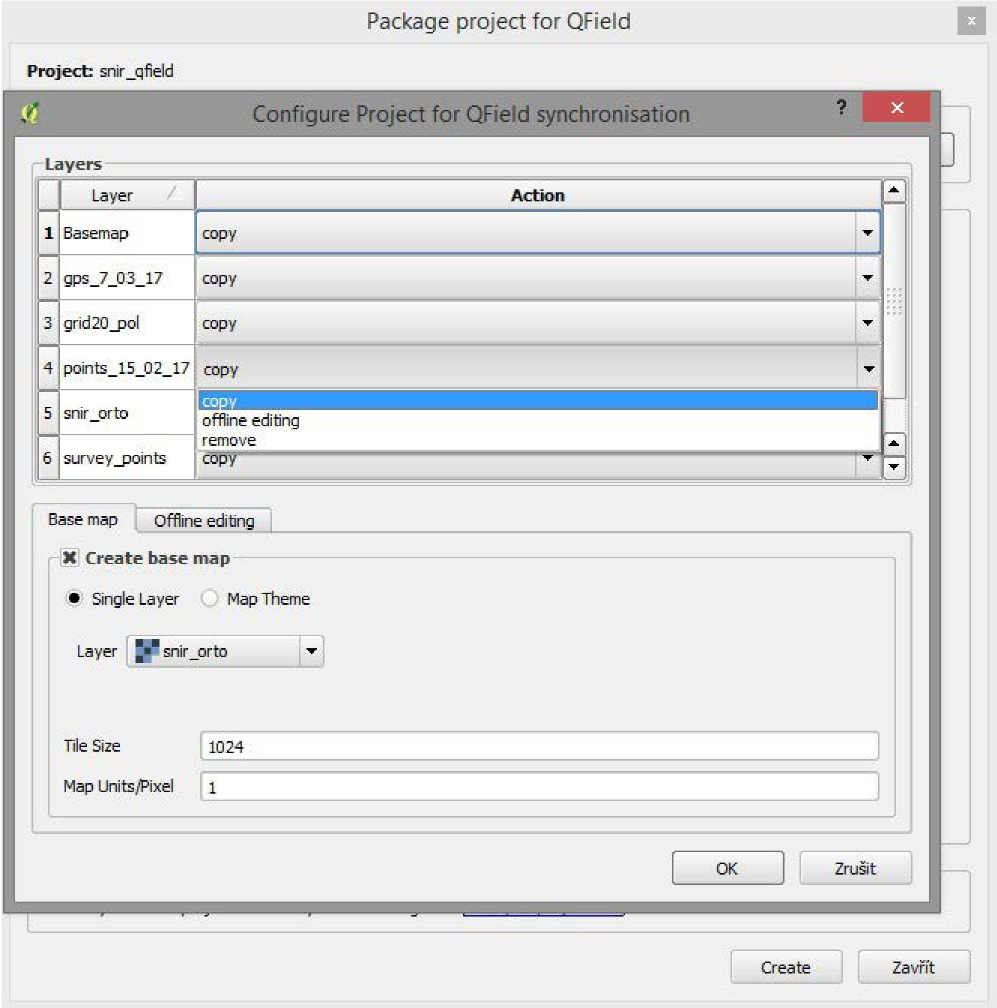

Figure 2. Configuration of the portable project using QFieldSync plugin.

device to computer (Fig. 2). The options are either to overwrite working copies or to update files on computer using changelog that keeps track of all the changes in the data done on the portable device.

Among supported data formats belong ESRI Shapefile, SpatiaLite and PostGIS (both SQL – Structured Query Language – databases supporting vector geometry), GeoPackage (geodatabase supporting raster data), WMS and MBTiles (web mapping services) and raster data (.tiff). In order to avoid working with huge raster data on portable devices with limited storage and memory space, raster layers can be converted to compact GeoPackage basemap.

The work in QField itself is based around two modes – browsing and digitizing. User can either browse the data put into the project earlier on desktop while in the field or he/she can digitize (create) new data. Since QField was designed from the start to be used as a field tool, the user interface is simplified to maximum extent and includes only essentials for fieldwork (Fig. 3). Everything – including layer selection, editing and digitizing new data is possible on regular touch screen.

In the first case study QField v0.8 was employed, which was upgraded to v0.10 before the start of the second case study. In both case studies choice was made to employ ESRI shapefiles for data storage and acquisition, despite some of its limitations, since the format is widely used and supported on all platforms.

During both case studies same mobile device was used: Lenovo tablet TAB 2 A10-70 (4 core CPU 1.7 GHz, 2 GB RAM, Android 5.01). In general, the GPS module in most recent cell phones and tablets is on par with common GPS handheld devices (Odolinski – Teunissen 2018), i.e. the deviation of measurements is on average around 2 m, which was deemed enough for extensive survey in the first case study.

The portable projects were built according to specific needs of each case study. They will be described in following sections in connection with research design.

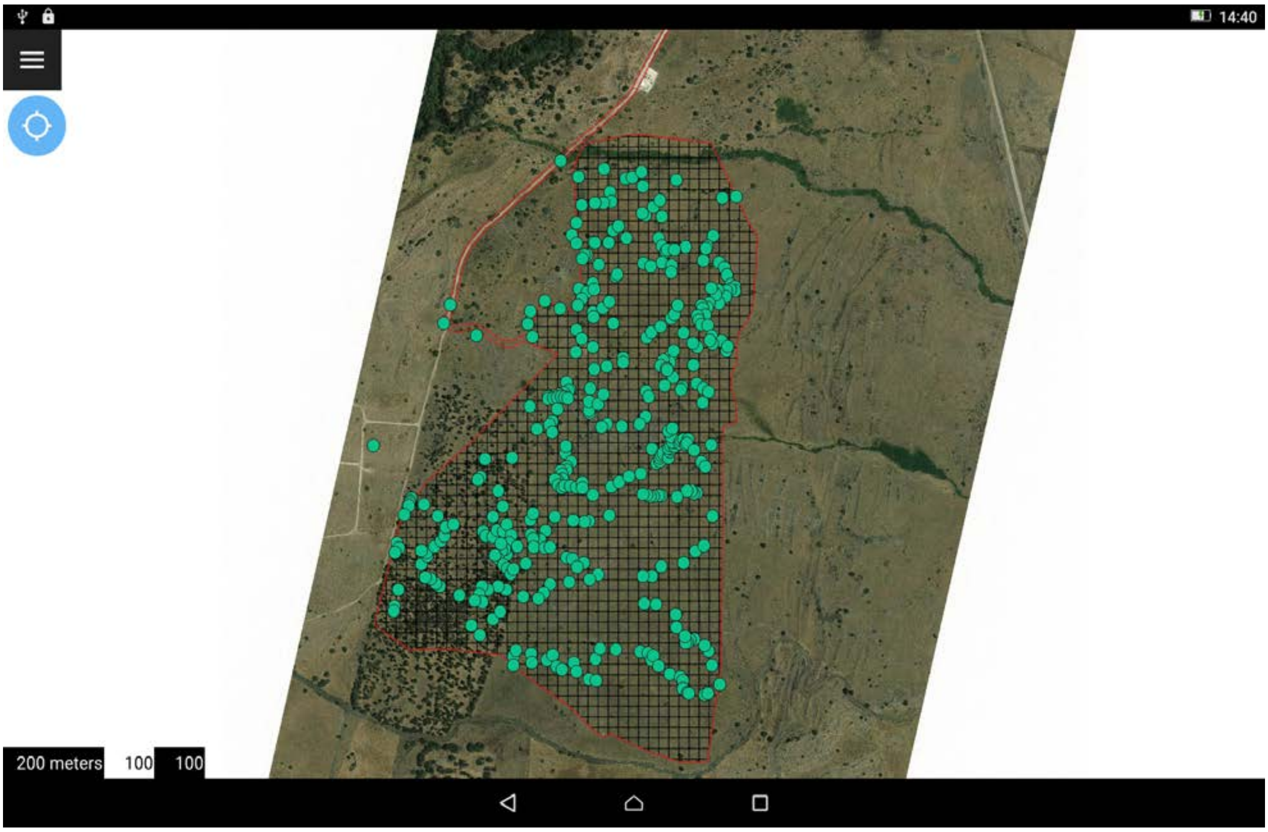

Figure 3. User interface (v0.8).

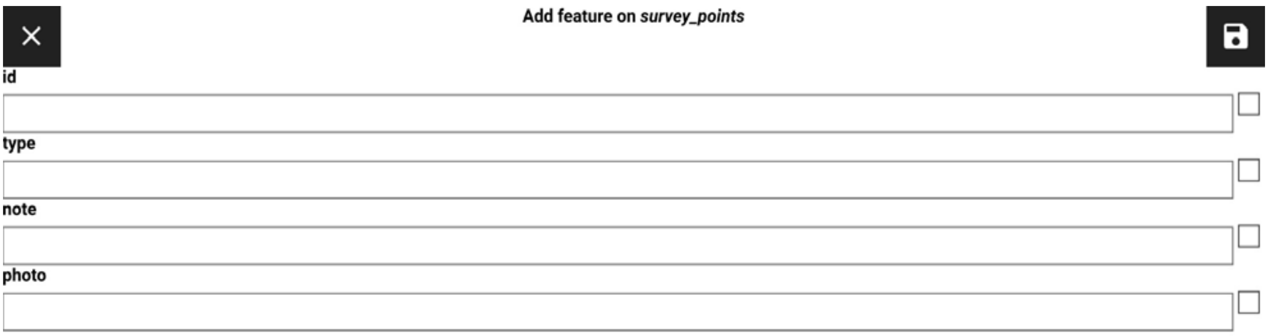

Figure 4. Digitize form of Khirbet es-Swade/Ma'agar Snir survey.

Case Study 1: Survey of Khirbet es-Swade/ Ma'agar Snir

The survey area covers some 52 ha and is located ca. 2 km south of ancient sanctuary and city of Caesarea Philippi-Paneas at the foot of Hermon Mountain in the northern Golan Heights (Fig. 3). The previous surveys recorded a site named Khirbet es-Swade with several ruined structures and pottery finds from Hellenistic, Roman, Byzantine, Mameluke and Ottoman periods, together with remains of Roman road leading from Paneas southwards including standing Roman bridge across Pera' stream (Epstein – Gutman 1972: 259, site no. 15; Hartal 2017, sites no. 66 and 70). However, Khirbet es-Swade overlaps with the survey area only in its south-eastern margins. The data at our disposal included georeferenced orthophoto of the area, kindly supplied by the construction company, and the polygon shapefile of proposed water reservoir to be built. The principal aim of the survey was to provide assessment of the archaeological potential of the area before its development.

From the orthophoto it was possible to identify linear features, probably representing agricultur-

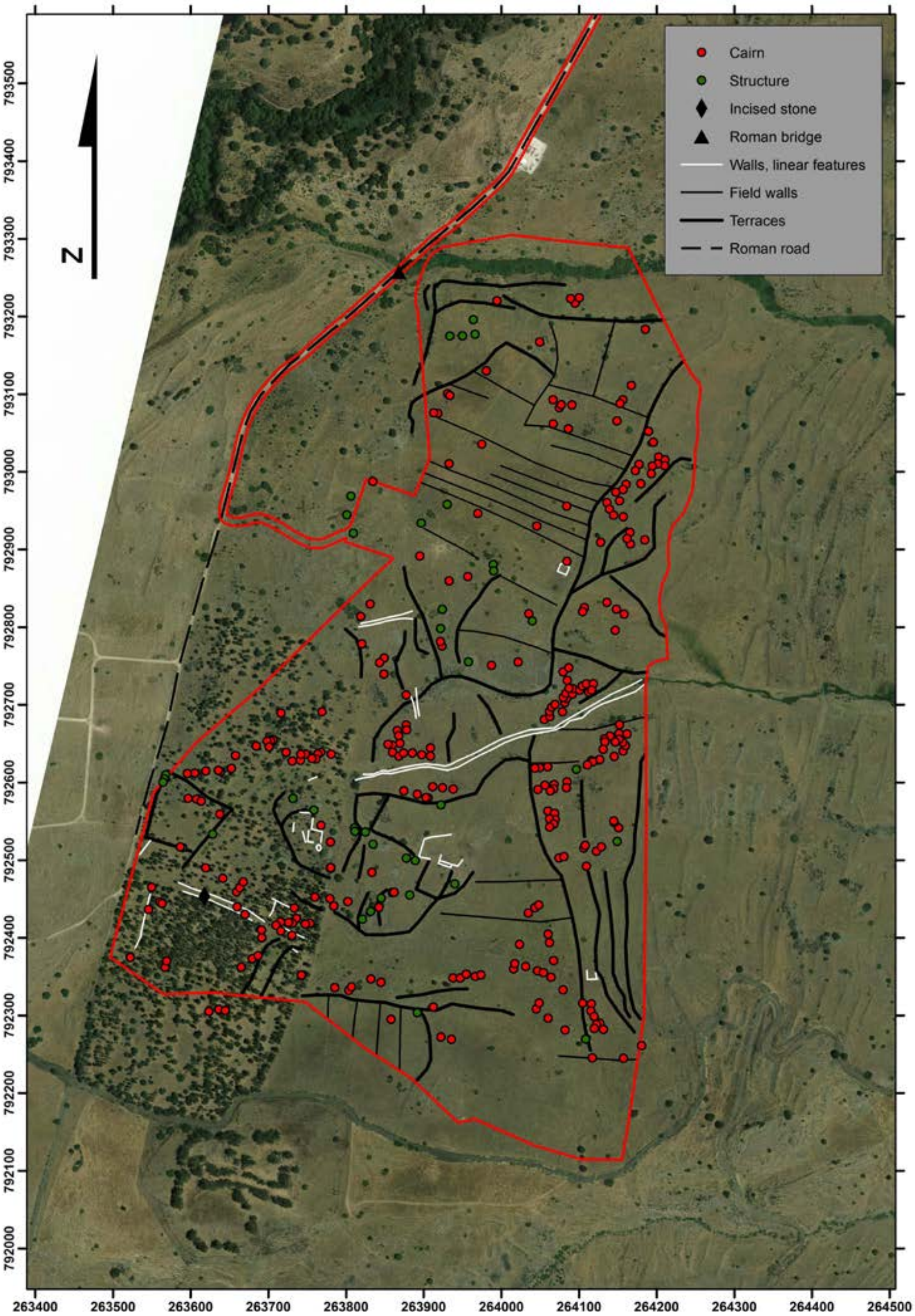

Figure 5. Visualisation of the results of the survey (Khirbet es-Swade/ Ma'agar Snir.

al terraces or field boundaries, several rectangular structures and dozens of small circular features apparently built of stones. Therefore, another goal of the survey was to verify these features, identify new ones and to carefully survey the forest in the southwestern part of the survey area, where no features could have been identified from the orthophoto.

The survey was designed as extensive, where all anthropogenic site and off-site features visible above ground are recorded. All of the area was covered by walking with a team of three to four people. The pottery and other small finds were not systematically collected although their presence was noted in the field.

The portable project for QField contains polygon shapefile defining the area of the survey, a 20 m grid for better orientation in the field, a blank survey point shapefile and the orthophoto of the area. Both approaches of working with raster data were tested – with original raster and with converted GeoPackage basemap. Survey point layer (Fig. 4) includes fields: id (number), type, note and photo

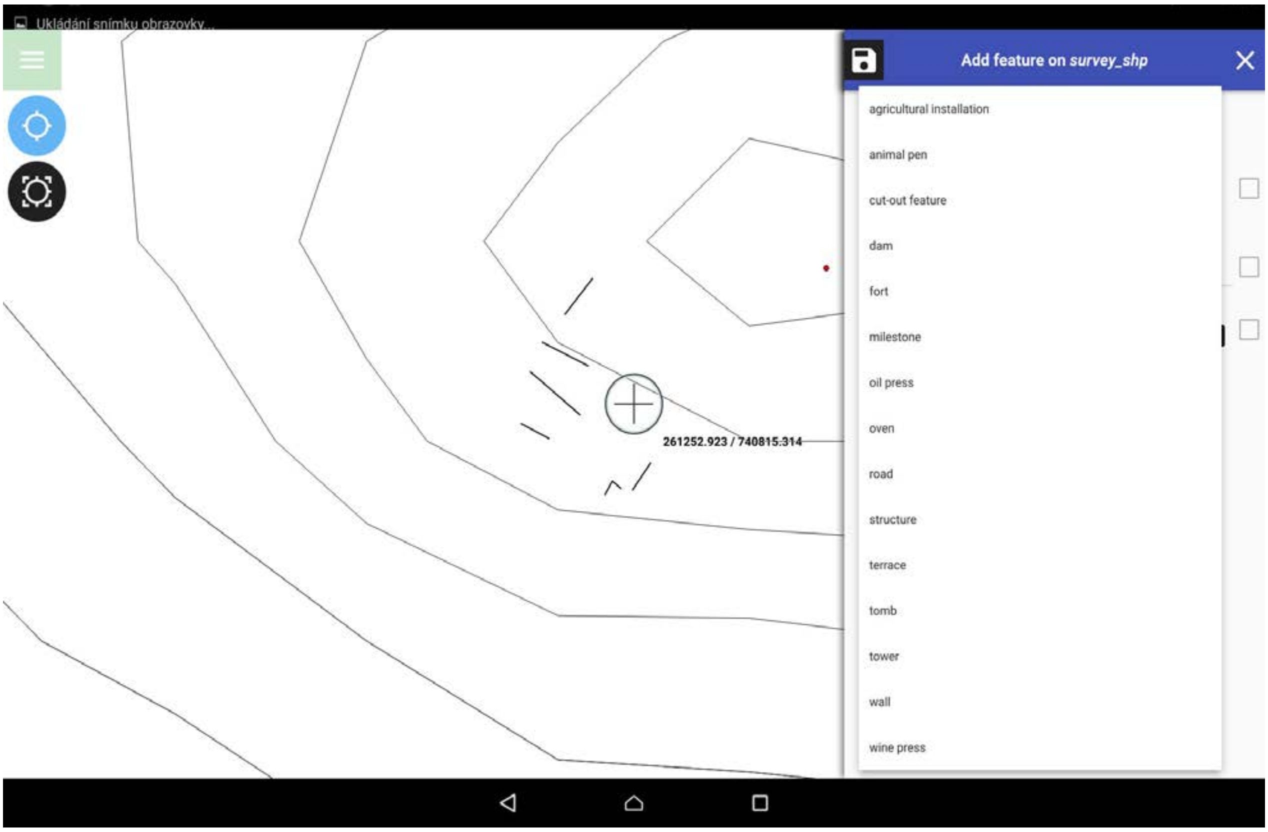

Figure 6. Drop-down list with pre-defined values.

(indicating if the feature was photographed). I.e. single features (such as cairns, ovens) are represented by one point whereas structures and linear features are represented by multiple points providing outline of the structures. Linear features could have been drawn in separate layer, but this was deemed to be too time consuming for the project, as the features were visible on the orthophoto and they only needed to be verified. The tick-box on the right of the fields (Fig. 4) can be crossed, so when creating new feature in the layer the last input values are automatically filled in.

After concluding the field work the survey shapefile was downloaded to desktop computer and opened in QGIS. The attributes in the type field were used for extraction of points pertaining to different structures (cairns, installations) and linear features (field walls, remains of buildings etc.) which were then drawn accordingly in separate shapefile. The data stored in the survey shapefile basically served as simple geodatabase for visualisation and post-survey analysis of the area (Fig. 5).

The area was surveyed in course of two days in February and March 2017. In total, 520 points were collected during the survey (Fig. 3). Among the surveyed features are agricultural terraces; field boundaries; a Roman/Byzantine tower; ruins of possibly two farmhouses, probably from medieval period; tentative agricultural installations in the fields, among those most prominent are shallow, partly dug out oval features, possibly kilns/ovens. Category of finds that stands out in the survey is presence of 283 stone cairns, varying in dimensions from 0.4–2.5 m in diameter to 0.4–1.7 m in height. However, their purpose and date are obscure.

Fast conclusion of the project was enabled mainly thanks to quick point acquisition and data input into the survey layer. This was achieved through the design of the survey shapefile and ergonomics of the program, minimising user's workload.

Case study 2: The Hellenistic and Roman Fortifications in the Territory of Hippos

The second survey is part of ongoing PhD research of the author, which is focused on Hellenistic and Roman period fortifications in the region of the city

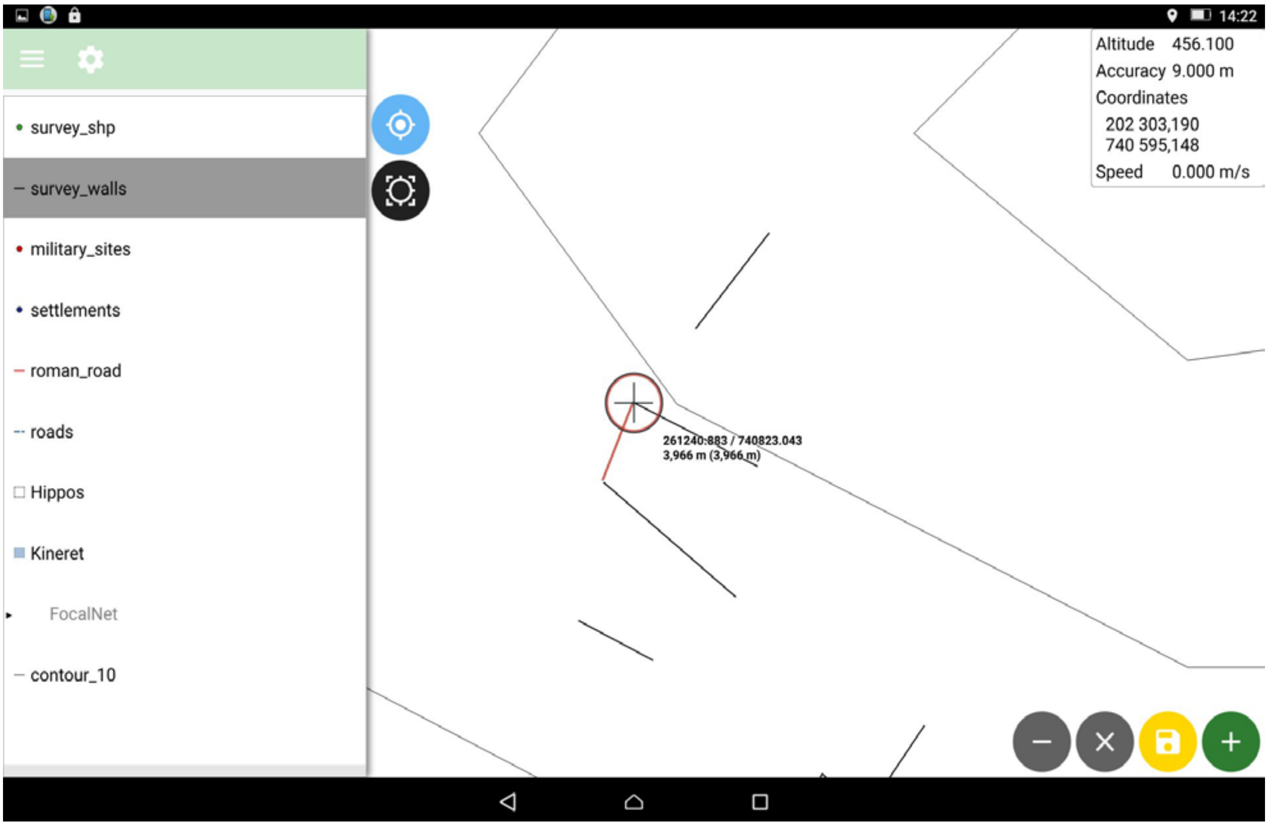

Figure 7. Line drawing, including distance measure (v0.10).SOLIDAR, IGN)

of Antiochia-Hippos in the southern Golan Heights. The goal of the survey is to record position of the sites, provide detailed plan of the structures, recording the masonry, building techniques and methods and survey of their environment, which may provide material for the dating of the sites.

Since the survey is still ongoing, only one example of the surveyed sites will be discussed below.

The portable project includes 1) contour map of the region 2) polygon delimiting the Sea of Galilee 3) line vector layer representing paths and tracks digitized from 1940s topographical maps with extant remains of the Roman roads and 4) two point vector layers representing sites from the database of the Archaeological Survey of Israel (one for settlement sites and one for fortified sites). For the data collection two vector layers were prepared: point vector layer for digitizing data on the surveyed sites together with on-site and off-site features whose type can be selected from drop-down list (prepared beforehand in QGIS; Fig. 6) and a line vector layer for drafting the walls of the structures. The point vector contained automatically filled FID and fields type, note and photo. Photo field allows for storing pictures taken by the Android device to be paired with given vector feature stored in a layer.

The surveyed site, called Zukey Kawarot, is located on prominent conical hill in the western piedmont of the Golan Heights. The site is composed of a large heap of ruined masonry on top of the hill (covering ca. 600 m2) and several installations on the northern slope. Thus, both point layer (data of single features) and polyline layer (walls) were used.

The survey of the site and its surroundings was again carried out very efficiently thanks to input of data through pre-defined values. The site drawing using line vector layer proved to be effective and, considerably precise (for the purpose of survey). Moreover, it can be used to measure distances as well (Fig. 7).

Major issue occurred during post-processing of the data. After exporting the survey data to desktop, it was attempted to pair site drawing with an orthophoto of the same structure generated from drone imagery (Fig. 8). The deviation of measurements of both GPS devices (tablet and drone) multiplies and creates large discrepancies which are not easily corrected without precise measurements.

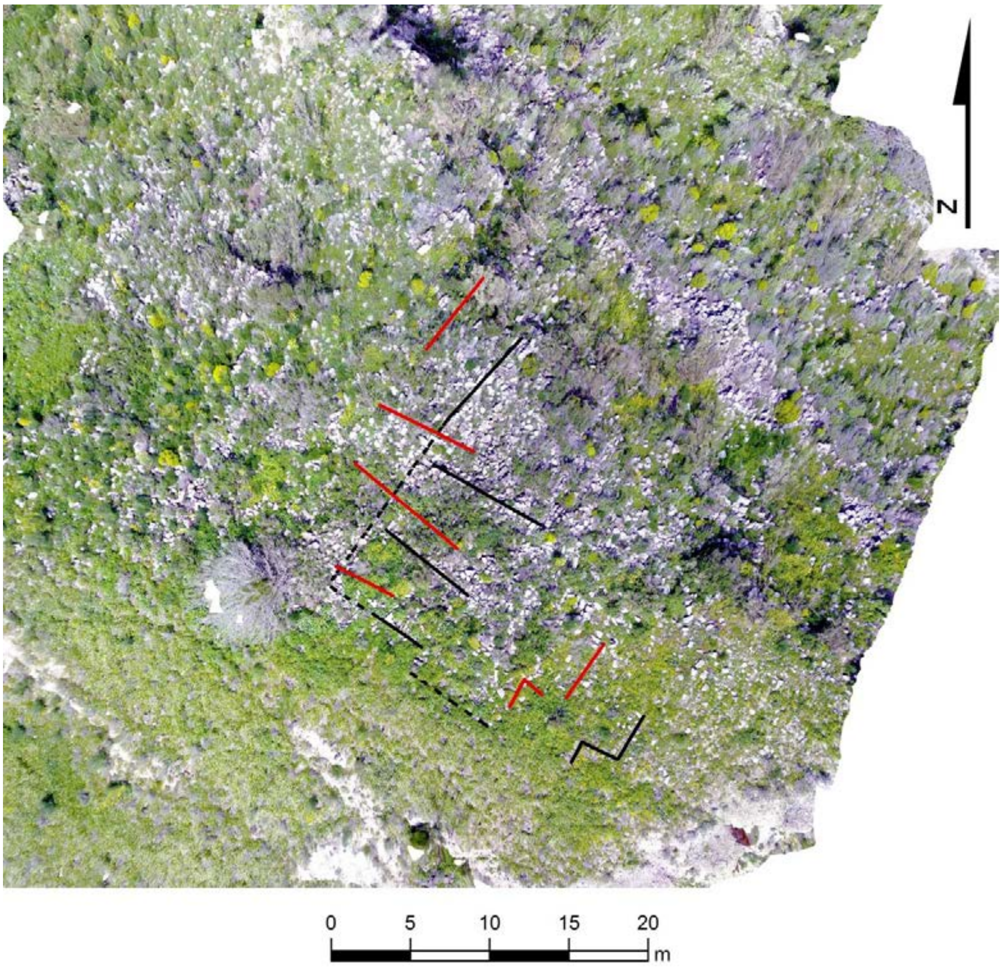

Figure 8. Discrepancy between walls drafted during survey (in red) and walls drafted on the orthophoto (in black), site of Zukey Kawarot.

Conclusions

The choice of QField as a F/OSS solution for archaeological survey was made in light of recent debate revolving around proper scientific conduct in research. The program was used for data collection in course of two extensive field surveys of in the Golan Heights in order to evaluate its potential for archaeological fieldwork focusing on three areas: 1) preparation and pre-processing; 2) data collection and field performance; and 3) data export and post-processing. In all three areas QField proved to be efficient and fast tool.

The filling out of attribute table for each survey point taken proved to be fast and straightforward mainly thanks to the possibility to use pre-filled values or drop-down lists. This shows that the careful preparation of the portable project improves performance of the surveyor in the field and could enhance the uniformity of data collected. The possibility to draw plans of surveyed structures and distance measurements directly in the field greatly contributed to the effectivity of the workflow and enhanced the precision of the drawings, as plan drafting is usually very time-consuming process and prone to inaccuracies caused by the drafters.

Even loading and displaying raster data (1.2 GB file representing orthophoto of the survey area in the first study case) was fast. Occasionally the program (v0.8) "froze" and tablet needed to be restarted. However, even if the program crashed, no data was lost; since each measured point must be stored before it is possible to continue, therefore only last point not yet stored might be lost. This problem seemed to improve greatly in later version (0.10) used in course of the second case study, which did not experience any crashes.

The major issue in post-processing appears to be incorporation with additional data obtained by different methods, such as combination of site drawing with an orthophoto generated from drone imagery in the second case study.

The compatibility and connection with desktop QGIS program made preparation of the portable project and (post-)processing of the collected data simple and straightforward especially for user already acquainted with GIS. The compatibility with widespread data formats (covering vector, raster and geodatabase formats), allows for transfer and work on the data across platforms when needed. All in all, QField is suitable tool for storing and recording archaeological data in the field in digital format without need to recourse to tedious paperwork.

Discussion

To summarize the performance of the QField solution it can be said:

1. Preparation and pre-processing: Workflow is fast, completely digital and can be done on one computer. The users acquainted with GIS will find no problems in configuring the portable project.

2. Data collection and fieldwork: Rightly configured portable project allows for fast and uniform input of data. The GPS provided appropriate spatial accuracy for extensive field survey and also good basic orientation in the field. The combination of outputs from various GPS devices, however, causes discrepancies. These could be overcome using ground control points (GCP) measured with the mobile device to rectify drone images. Occasional instability of the program (previous version) did not resulted in loss of data.

3. Data export and post-processing: Migration of data between portable device and computer is done typically through cable or wireless connection. Once opened on desktop in QGIS the data needs little to none editing as they are already stored in pre-defined GIS-compatible files. Therefore, errors and inaccuracies stemming from conversion are eliminated. This leaves more time for actual post-survey analysis.

QField proved to be useful and efficient tool for field survey. Generally, program's performance during fieldwork is smooth and fast. Preparation of portable project may not seem as straightforward for unskilled users, but extensive user guide is available online. The support of common data formats (such as shapefile) makes it easy for collected data to be transferred and used on variety of platforms and software (both proprietary and F/OSS) with practically no editing necessary. Moreover, support for SpatiaLite and PostGIS – SQL databases – means these could be used, theoretically, not only for extensive or intensive survey, such as pottery collecting in pre-defined squares, but also for paperless documentation of excavations. The issue that needs to be addressed is how it would be possible to connect/synchronize several devices, so that more than one person can work on the project in course of the fieldwork. In that way, an extensive survey consisting of several teams could work in fast and efficient way; while at the same time team members could control and check on the job of the others.

The main advantages of QField are a) low cost; b) offline operation; c) ergonomics of touch-screen operation; d) customization of portable project; e) support of wide range of GIS compatible formats; f) interoperability with desktop applications without need to convert data.

Especially the user customization of the portable project is crucial for archaeological fieldwork as each project can be tailored to suit specific research design.

Among the disadvantages of the program can be counted poorer support of raster formats (apart from web mapping services it supports only .tif and GeoPackage). Another weakness is not connected with the program. It is the hardware limitation of the GPS receiver which often creates large inaccuracies where more precision would be needed (e.g. site drawing). And, as it was shown in the second case study, it makes combination of data collected through multiple GPS devices problematic. This might be alleviated by using GCP measured with one device only (or with introduction of better technologies in the future perhaps). Further, as of now, there is no support for iOS devices.

I am confident that the future of 'free and open source software' and mobile GIS in archaeology is bright.

Acknowledgments

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References

Averett, E W and Gordon, J M and Counts, D B (eds.) 2016 *Mobilizing the Past for a Digital Future: The Potential of Digital Archaeology.* Grand Forks: The Digital Press University of North Dakota.

Ducke, B 2012 Natives of connected world: free and open source software in archaeology. *World Archaeology*, 44(4): 571-9. DOI: 10.1080/00438243.2012.743259

Ducke, B 2015 Free and Open Source Software in Commercial and Academic Archaeology: Sustainable Investments and Reproducible Research. In: A.T. Wilson – B. Edwards (eds.): *Open Source Archaeology: Ethics and Practice.* De Gruyter Open Access, pp. 92-110. DOI: 10.1515/9783110440171

Epstein, C and Gutman, S 1972 The Survey in the Golan Heights. In: Kochavi, M and Epstein, C (eds). *Judaea, Samaria and the Golan: Archaeological Survey in 1967–1968*. Jerusalem: Carta, pp. 243–298 (in Hebrew).

Hartal, M 2017 *Map of Dan (8)*. Available at: http://survey.antiquities.org.il/index_Eng.html#/MapSurvey/2177 [Last accessed 1/8/2018].

Odolinski, R and Teunissen, P J G 2018 An assessment of smartphone and low-cost multi-GNSS single-frequency RTK positioning for low, medium and high ionospheric disturbance periods. *Journal of Geodesy*, 93:701-722. DOI: 10.1007/s00190-018-1192-5

Orengo, H 2015 Open Source GIS and Geospatial Software in Archaeology: Towards their Integration into Everyday Archaeological Practice. In: Wilson, A T and Edwards, B (eds.). *Open Source Archaeology: Ethics and Practice*. De Gruyter Open Access, pp. 64-82. DOI: 10.1515/9783110440171

Tripcevich, N and Wernke, S A 2010 On Site Recording of Excavation Data Using Mobile GIS. *Journal of Field Archaeology*, 35(4): 380-397. DOI: 10.1179/009346910X12707321242511

Wagtendonk, A J and De Jeu, R A M 2007 Sensible Field Computing: Evaluating the Use of Mobile GIS Methods in Scientific Fieldwork. *Photogrammetric Engineering & Remote Sensing*, 73(6): 651-662.

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Martina Trognitz
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Evaluation of Tools for Clustering of Archaeological Data

Martina Trognitz
Austrian Academy of Sciences
martina.trognitz@oeaw.ac.at

Abstract

Dedicated clustering programs, preferably with graphical user interfaces, are a useful alternative for those not very well acquainted with programming languages. In the last decades a variety of ready-to-use tools were developed, of which a freely availlable selection was evaluated in regard to their suitability for archaeological data, the number of functions and ease of use. This task was done with a dataset describing Aegean seals.

Keywords: clustering, clustering programs, evaluation of tools

Introduction

A common task in archaeology consists in subdividing large sets of seemingly similar artefacts, such as pots, stone tools or coins, into smaller groups of objects with distinct features. By classifying objects into groups, a typology is created. This process can be automated by the means of cluster analysis, an unsupervised machine-learning technique. With the increasing availability of computers from the sixties onwards, clustering was also tested and applied in the archaeological field (Baxter 1994: 2; Hodson 1970: 299-300).

In the last decades a variety of ready-to-use tools and programs for cluster analysis were developed, of which a selection was evaluated in regard to their suitability for archaeological data. This task was done with a dataset describing Aegean seals.

First, an introduction to cluster analysis is given in the next section. It is then followed by a section with a more in detail description of the data set, after which, the evaluated tools are presented. A summary of the evaluation of clustering programs is given in Table 1.

Cluster Analysis

In statistics, clustering is part of multivariate analysis methods (Drennan: 309), whereas it is also described as a part of machine learning or data mining (Kumar, Steinbach & Tan 2006: 6-7). With cluster analysis, a set of objects can be grouped into distinct groups of similar entities solely based on the objects' descriptive variables. It is thus also referred to as an unsupervised machine learning method or, more specifically, an unsupervised classification method (Kumar, Steinbach & Tan 2006: 490-491).

A vast number of clustering algorithms for different needs, aims, and data sets are available to choose from. Popular clustering algorithms include k-means and hierarchical clustering, which do also represent the two distinct clustering types: partitional and hierarchical. K-means belongs to the former group and divides a data set into groups without overlaps. Hierarchical clustering produces nested clusters, by linking smaller groups into superordinate groups (Kumar, Steinbach & Tan 2006: 491-492).

Though a great variety of clustering algorithms exists, they all have in common that similarity (or

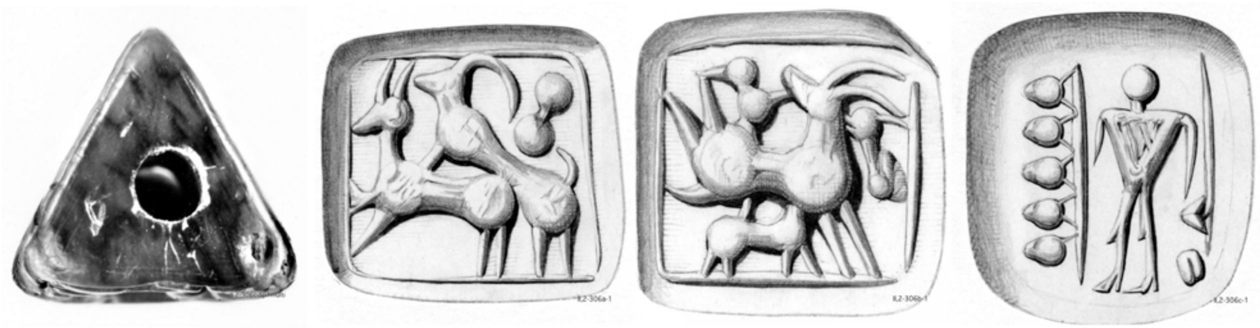

Figure 1. The three-sided prism CMS II,2 306 and drawings of its three sides.

dissimilarity) measures are used to calculate how similar (or different) two objects to be compared are (Kumar, Steinbach & Tan 2006: 65; Drennan 2009: 271). The higher a similarity coefficient is, the more alike two objects are.

Not all similarity measures are applicable to all data types. The Euclidean distance (Drennan 2009: 272-277), e.g., is not suitable for nominal values, whereas the Jaccard coefficient (Drennan 2009: 277-279) is. The Gower distance (Drennan 2009: 280) can be used for numeric, nominal, and binary (or dichotomous) values.

Data Set

The used data set describes 1033 Aegean seals with more than one face for sealing, i. e. multi-sided seals. The seals are small objects made of stone, bone or ivory and come in various shapes, such as lentoids, cylinders, cubes or triangular prisms. Most of the seals originate from Bronze Age Crete (Minoan seals) and mainland Greece (Mycenean seals). Their dating ranges from 3000 to 1100 BCE.

The information was harvested from the freely accessible database Arachne (http://arachne.uni-koeln.de) where all Aegean seals documented in the „Corpus der Minoischen und Mykenischen Siegel" (CMS) (http://cmsheidelberg.uni-hd.de/) are recorded. Each seal is described with about fifty attributes organised into eleven thematic groups: „identification", „provenience", „shape", „material & technique", „measurements & preservation", „general information about decoration", „stylistic classification", „ornaments", „characters", „figurative motifs excepting creatures" and „creatures".

The attributes contain numeric (interval and ratio), binary, ordinal, geographic and nominal values. With the help of the three-sided seal CMS II,2 306 in Figure 1, examples for each data type are given and illustrated in the following subsections.

Numeric Attributes

Numeric data types in the used data set belong to the thematic groups „measurements & preservation" and „creatures". They include the number of sides a seal has, dimensions (e. g. width or length) and a computed count of all creatures depicted on one seal. For the example in Figure 1, the values are 3, 1.1 cm and 1.2 cm, and 7, accordingly.

Binary Attributes

Originally the data set did not contain any binary attributes. During processing, a new attribute was introduced based on the attribute's values listing all used script characters. It denotes if script is present on a seal or not, thus only assuming either 0 (no script) or 1 (use of script). On CMS II,2 306 no script (=0) is used.

Ordinal Attributes

Ordinal attributes can be found in the thematic groups „provenience", „material & technique", and „stylistic classification". They are used to indicate a seal's dating using a relative chronology, such as MM II for CMS II,2 306, which stands for the second phase of the Middle Minoan period. Periods in the chronology of the Aegean Bronze Age are not of equal length, and absolute dates are still a matter of debate (Krzyszkowska 2005: 11).

A seal's material class in the original data set is given with nominal values, but its equivalents on the Moh's scale were introduced during processing. For the example seal, the value equals 2, which stands for soft stone.

Geographic Attributes

Geographic coordinates indicate where a seal was found and are given with longitude and latitude, e. g. 23.71622 and 37.97945.

Nominal Attributes

Nominal values are used for most of the attributes to describe a seal's shape, depicted creatures, objects or ornaments, and for listing the different engraved script characters. The shape of the example in Figure 1 is described with „Dreiseitiges Prisma" (three-sided prism).

Evaluation of Clustering Tools

Although dedicated libraries for programming languages like Python or R exist, clustering programs, preferably with graphical user interfaces, are a convenient alternative for those not very well acquainted with programming languages.

Criteria

The selection presented here ranges from simple programs with single functionalities to full-blown statistic environments able to set up custom workflows. The most significant selection criterion was free availability, which is why any software not free of charge was excluded from the evaluation.

The evaluation focused on overall functionalities and handling of programs as opposed to performance and clustering results. The latter is a subject of its own and would require a data set with already known clusters. An example of how the evaluation of clustering algorithms might be executed is shown in the works of Hodson, Sneath & Doran (1966) and Hodson (1970), which also includes a small data set of Iron Age fibulae.

Tests were run on a computer with Xubuntu 16.4 and partially on a virtual machine with Windows XP. Because the k-means algorithm is supported by all programs, this was used to test importing, parameter setting, actual clustering, visualisation and exporting of results to get a feeling for the programs.

The considered programs, are presented in order of their latest version with the oldest first. A tabular summary of each program's features is given in Table I. Each row represents evaluation results for one program. The first column displays the latest version of the software and the year that it was released. In the next three columns the supported operating systems are listed.

Of all tested programs, only CLUTO did not have a graphical user interface (GUI) because the respective package could not be executed. The columns installation, technical, manual, and training are all concerned with documentation: Are installation guidelines available and useful? Is there extensive technical documentation? Does there exist a manual and is further training material provided?

How large and active the community using a specific tool is, is a good indicator of how easy it is to get help or alternative tutorials. This is indicated in a separate column.

The actual functionalities provided by each program are indicated with the import and export formats, the supported data types (numerical, ordinal or nominal), the number of algorithms and similarity measures available and visualisation as well as validation capabilities of the results.

Cluster 3.0

Cluster 3.0[1], a program originally written by Michael Eisen at Stanford University, is a cluster program for analysing genome datasets which uses the C Clustering Library 1.54.

It offers a GUI, but can also be used on the command line. Three clustering algorithms are provided, of which the first one, hierarchical clustering, offers four variants, thus effectively offering six algorithms. Also, principal component analysis (PCA) is available. Eight similarity measures are provided and described in detail in the manual (four variants of the Pearson correlation, Spearman rank, Kendall's τ, Euclidean distance, and the city-block distance).

Cluster 3.0 can only process numerical data and

1 http://bonsai.hgc.jp/~mdehoon/software/cluster/software.htm; Manual is available at http://bonsai.hgc.jp/~mdehoon/software/cluster/cluster3.pdf

this has to be provided in a tab-delimited txt-file. After the import values can be further filtered and adjusted. ‚Genes' refers to the rows, while ‚Arrays' takes into account the data in a column.

Results are stored in different text-based output files. When using k-means for 'genes', a cdt and a kgg file are created. In the cdt file, the rows of the original file are rearranged according to the clusters the objects were assigned to. Some additional columns and rows are inserted, but the meaning of those is not described in the manual. The kgg file contains the object identifier and the cluster number it was assigned to.

The software lacks a general overview of cluster results, e.g. how many objects each cluster has. A visualisation of results is only available for results achieved with hierarchical clustering and with the TreeView software.[2]

CLUTO

CLUTO[3], the CLUstering TOolkit, was developed for the clustering of documents by George Karypis at the University of Minnesota. It can be used to cluster low and high-dimensional datasets.

It is command line based, but with gCluto (2003), which unfortunately did not work on Xubuntu 16.04, a GUI is offered as well. Furthermore, the program can be used as a stand-alone C or C++ library. CLUTO offers the vcluster and scluster programs to cluster data in k clusters. With vcluster each object is treated as a vector in high-dimensional space, while with scluster clustering is done by calculating the similarity space between the objects.

Of the six clustering algorithms provided, four are partitional and the remaining two are agglomerative (or hierarchical). The user has four similarity measures to choose from, as well as seven different criterion functions for finding the clusters.

Data has to be provided either as a MatrixFile for vcluster or as a GraphFile for scluster.

The manual provides information on how to format these files. Many examples for executing CLUTO are also provided in the manual. CLUTO can only process numerical data.

Results are directly displayed in the command line, and multiple options exist to fine-tune the output. The output also contains internal and external cluster quality statistics, which also serve as validation or evaluation of the clusters; the former is based on the clustering criterion function, and the latter is based on external measures provided by the user.

Two files representing the result are created as well. The actual clustering outcome is stored in the clustering solution file <orig-filename>.clustering.<k>, which contains n lines with a single number representing the cluster an object belongs to. The visualised tree is stored in <orig-lename>.cltree.<k> and contains 2k - 1 lines containing the parents of the nodes with further values describing similarities. Visualisations of the results can be exported in various graphic file formats.

ELKI

ELKI[4] - Environment for Developing KDD-Applications Supported by Index-Structures is a JAVA-based program developed at the Data Science Lab of LMU Munich with research on clustering in focus.

Data can be imported in its own ELKI format, as arff or as libSVM. Custom import settings allow accommodating other file formats. The GUI provides a tabular view to select and set the wished parameters for clustering. This creates a command, which can then be executed from within the interface. Upon execution, a visualisation window with an overview of graphs is displayed. The graphs can be explored individually. Exporting data is only possible into a set of txt files compatible with GNUPlot.

The extensive documentation offers a few tutorials to allow for a quick start. But for the proper use and full understanding, good theoretical knowledge about cluster analysis and its related concepts is required.

Algorithms and distance measures can be extended, which would also allow to process ordinal and nominal values.

2 https://jtreeview.sourceforge.net/

3 http://glaros.dtc.umn.edu/gkhome/cluto/cluto/overview

4 https://elki-project.github.io/

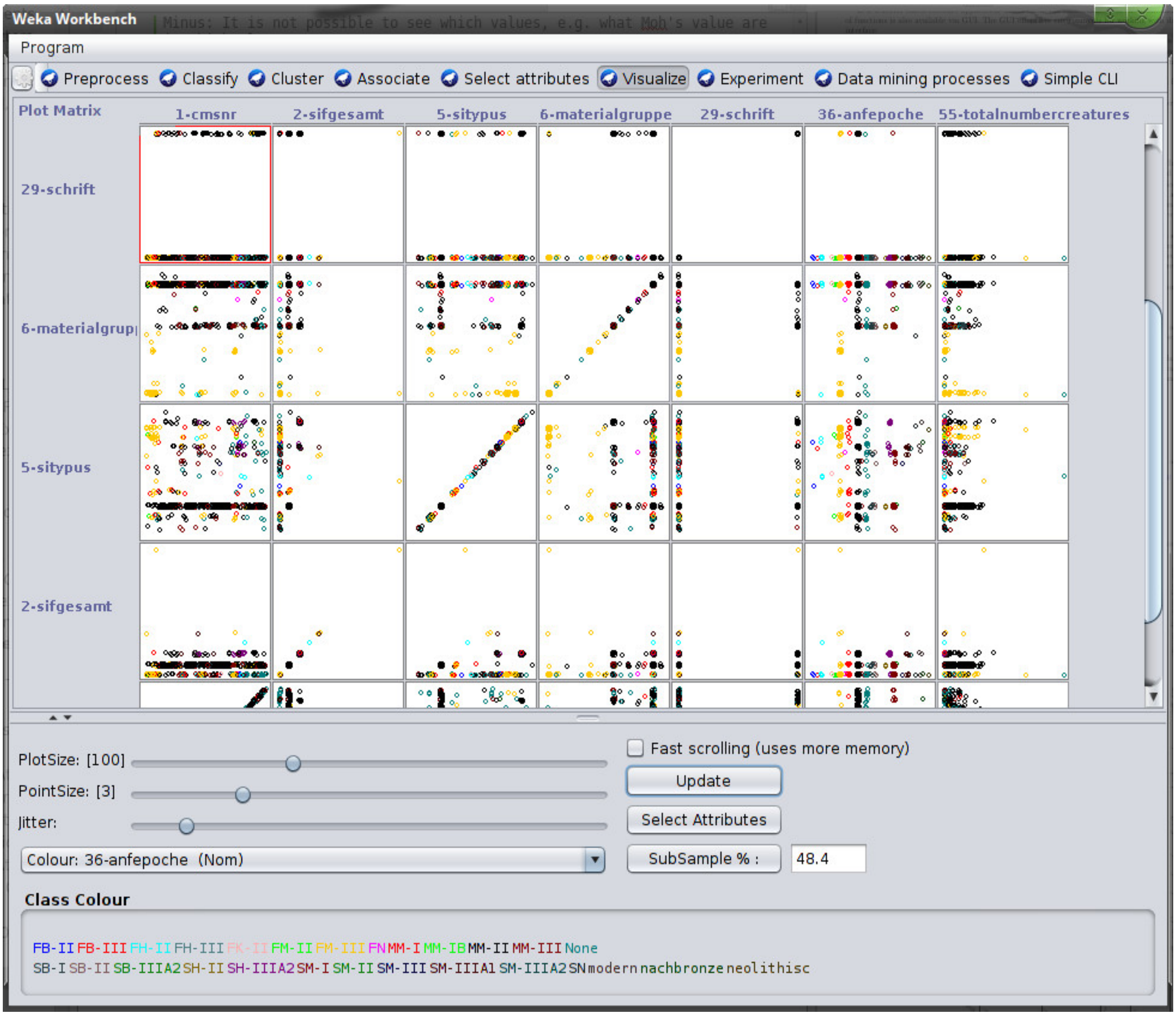

Figure 2. Multiple scatterplots for different attribute pairs in Weka.

jMinHep

jMinHep[5] provides three clustering algorithms and is a JAVA-based program developed by S. Chekanov. It is part of the DataMelt environment[6] but is also available as a standalone application.

Data has to be imported in a slightly modified arff file format. Arff files can be converted from a csv file with online tools[7] and for jMinHep the separating commas have to be replaced by spaces. Only numeric values can be processed and all other data types should be removed from the import file to avoid errors.

Results are visualised as a graph either representing single data points or density. These graphs can be exported as pdf. A more informative result with data points and the clusters assigned, can be opened by clicking on "show result" and saved as a txt file.

The application is not supported anymore and documentation about it on DataMelt has limited access.[8]

5 http://jwork.org/jminhep/
6 https://datamelt.org/
7 E. g. https://ikuz.eu/csv2arff/
8 https://handwiki.org/wiki/DMelt:AI/Data_Clustering

	Windows	Mac OS	Linux	Latest Version	GUI	installation	technical	manual	training	community	Import	numerical	ordinal	nominal	No. of Algorithms	No. of Similarity Measures	Visualisation	Cluster Validation	Exporting
Cluster 3.0	✓	✓	✓	3.0 (2002)	✓	✓	-	✓	-	-	tab-delimited text files particular format	✓	-	-	$1 \times 4 + 2$	$1 \times 4 + 4$	~	-	set of text files (cdt, gtr, atr, kgg, kag, txt, gnf, anf)
CLUTO	✓	✓	✓	2.1.2 (2006)	~	✓	-	✓	✓	-	own text based format	✓	-	-	6×2	4	✓	✓	Visualisations as image files; results as text files
ELKI	✓	✓	✓	0.7.1 (2011)	✓	✓	✓	✓	✓	-	own text based format, arff, libSVM	✓	~	~	> 14	> 23	✓	✓	txt files compatible with GNUPlot
jMinHep	✓	✓	✓	2.0 (2013)	✓	-	-	~	-	-	arff	✓	-	-	3	1	✓	-	pdf, txt
TANAGRA	✓	-	-	1.4.5 (2014)	✓	-	-	-	✓	-	tab-delimited text files, xls, arff, libSVM, dat, data	✓	-	✓	4 (14)	?	✓	~	txt
WEKA	✓	✓	✓	3.8 (2017)	✓	✓	✓	✓	✓	✓	arff, csv, C 4.5, libsvm, JSON, databases	✓	✓	✓	$6 + 2$	$4 + 1$	✓	-	arff, txt
PAST	✓	✓	-	3.19 (2018)	✓	✓	✓	✓	-	~	(tab, space, comma) separated txt, dat, xls	✓	✓	✓	3	23+	✓	-	dat, txt, xls, nex, tps, nts, fas, rft, dic, graphic formats, pdf

Table I: Summary of the evaluation of clustering programs (2018).

TANAGRA

Tanagra[9] was developed by Ricco Rakotomalala. It is a data mining software providing different data mining methods from exploratory data analysis, statistical learning, and machine learning.

The software runs on Windows (the author claims it can also be executed with WINE on Linux) and comes with a GUI on which the user can create a stream diagram with several components for different tasks. Numeric and nominal data can be imported from tab-separated txt files or xls, arff, libSVM, dat or data files.

Testing clustering with only numerical values was successful, and although in theory clustering of nominal values should be possible it could not be achieved in practice. For clustering 14 options, which presumably represent variants of a total of four clustering algorithms are available. No similarity measure can be chosen.

Results can only be exported as a txt file and be visualised in the program. Visualisations cannot be exported and the lack of systematic documentation does not allow to fully understand what the program is capable of.

WEKA

Weka[10], the Waikato Environment for Knowledge Analysis, was developed at the University of Waikato as a workbench for machine learning.

It is a Java-based software application which offers full functionality via the command line interface. A large set of functions is also available via a GUI. The GUI offers five environments for creating stream diagrams for custom data workflows, including a command-line interface.

Testing was done by using the explorer environ-

9 https://tanagra-machine-learning.blogspot.com/ and http://data-mining-tutorials.blogspot.co.at/search/label/Tanagra and http://tutoriels-data-mining.blogspot.com/

10 https://www.cs.waikato.ac.nz/ml/weka/index.html

ment, but available algorithms and functionalities also apply to the remaining environments. Data can be imported in arff, csv, C4.5, libSVM and JSON format. Further editing, adjustment, filtering and transforming of data are supported. Weka can process numeric, nominal, ordinal, binary, dates and string data types. It is also possible to work with data from a remote database.

Six different algorithms (and two additional variants) and four (plus a user-defined filter) similarity measures are available for hierarchical and k-means clustering.

The general output of the clustering process is displayed in the GUI, which also provides a list of scatterplots for a quick overview, as shown in Figure 2. Furthermore, concise information about the functions is presented to the user when hovering over the respective buttons. Data with cluster assignments, can be exported in arff format. Visualisations cannot be exported.

PAST

PAST (PAleontological STatistics)[11] is a statistics software package developed by Øyvind Hammer at the Natural History Museum and the University of Oslo. The software offers a GUI literature references for the available methods and measures. Tabular data can be imported as a tab-, space- or comma-separated txt file, as dat, or as xls. Further operations and transformations are available, although a function is missing to convert nominal values in string format into a numeric format. For each column, a data type (unspecified, ordinal, nominal, binary, string, and group) can be selected. This step has to be done to enable the clustering of mixed data types.

Three clustering algorithms can be selected, and except for k-means a selection from 23 similarity measures is possible. The user can also provide a custom similarity measure or select different measures for mixed data types.

Results are displayed in a separate view which allows exporting in the nexus format. Visualisations of the resulting trees can be exported in various graphic formats. Exporting results from k-means is limited, and no cluster validation is provided.

11 https://www.nhm.uio.no/english/research/resources/past/

Not Tested

There exist more tools, which are worth a look. For example, an open-source alternative of SPSS capable of doing k-means clustering called PSPP[12] exists. A similar system is SOFA - Statistics Open For All[13] or KNIME[14].

Some GUI programs are based on Python or R, such as Orange[15] or Rattle[16], which were specifically made for data mining.

And finally, an online tool should also be mentioned: clustVis[17]. It cannot cluster data, but it can be used for principal component analysis.

Conclusion

Though an archaeological dataset typically consists of numerical, nominal and spatial data, most clustering applications require the data to be described with numerical values.

From the seven evaluated programs Weka and especially PAST offer all necessary functionalities for processing archaeological data out of the box and easy understandable interfaces. For the more advanced users ELKI also poses a useful application, due to the possibility to use custom algorithms and similarity measures.

If one wants to have full control, more options, and complete flexibility using respective packages in Python or R might be the better way to go.

The article was finalised in 2018. For the publication in the proceedings the links were checked and updated. As of March 2023, new releases for ELKI, Weka, and PAST were available.

12 https://www.gnu.org/software/pspp/
13 http://www.sofastatistics.com/home.php
14 https://www.knime.com/
15 https://orangedatamining.com/
16 https://rattle.togaware.com/
17 https://biit.cs.ut.ee/clustvis/

References

Baxter, M J 1994 *Exploratory Multivariate Analysis in Archaeology.* Edinburgh: University Press.

Drennan, R D 2009 *Statistics for Archaeologists: A Common Sense Approach*. Boston, MA: Springer. DOI: 10.1007/978-1-4419-0413-3

Hodson, F R 1970 Cluster Analysis and Archaeology: Some New Developments and Applications. *World Archaeology*, 1(3): 299-320. Available at https://www.jstor.org/stable/124057 [Last accessed 23 March 2023].

Hodson, F R, Sneath, P H A and Doran, J E 1966 Some experiments in the numerical analysis of archaeological data. *Biometrika*, 53(3-4): 311-324. DOI: 10.1093/biomet/53.3-4.311

Krzyszkowska, O 2005 *Aegean Seals: An Introduction.* London: Inst. of Classical Studies, School of Advanced Study, Univ. of London.

Kumar, V, Steinbach, M and Tan, P-N 2006 *Introduction to Data Mining.* Boston: Pearson Addison Wesley.

Pedregosa, F, Varoquaux, G, Gramfort, A, Michel, V, Thirion, B, Grisel, O, Blondel, M, Prettenhofer, P, Weiss, R, Dubourg, V, Vanderplas, J, Passos, A, Cournapeau, D, Brucher, M, Perrot, M and Duchesnay, E 2011 Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research,* 12: 2825-2830. Available at https://www.jmlr.org/papers/volume12/pedregosa11a/pedregosa11a.pdf [Last accessed 23 March 2023]

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Using ABM to Explore the Role of Socio-Environmental Interactions on Ancient Settlement Dynamics

Frédérique Bertoncello
Université Côte d'Azur, CNRS, CEPAM - UMR 7264 CNRS,
frederique.bertoncello@cepam.cnrs.fr

Marie-Jeanne Ouriachi
Université Côte d'Azur, CEPAM - UMR 7264 CNRS,
marie-jeanne.ouriachi@univ-cotedazur.fr

Célia da Costa Pereira
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
celia.da-costa-pereira@univ-cotedazur.fr

Andrea Tettamanzi
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
andrea.tettamanzi@univ-cotedazur.fr

Louise Purdue
Université Côte d'Azur, CNRS, CEPAM - UMR 7264 CNRS,
louise.purdue@cepam.cnrs.fr

Rami Ajroud
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
ajroud.rami@hotmail.fr

Jérémy Lefebvre
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
lefebvre.jeremyp@gmail.com

Abstract

This paper presents a work in progress within the project « Modeling the role of socio-environmental interactions on Ancient Settlement Dynamics - ModelAnSet » developed by archaeologists, historians, palaeoenvironmentalists and computer scientists at University Côte d'Azur (Nice). Agent-based modelling is used to explore the respective role of environmental and social factors in the evolution of the settlement pattern and dynamics during the Roman period in South-Eastern France. The model aims at simulating the impact of the climatic and macro-economic conditions on the behaviour of Gallo-Roman landowners. According to the profit they derive from their farms and/or villas, which depends both on natural and socio-economic factors, the landowners can decide to maintain without change, improve, enlarge or abandon their agricultural holdings or to create a new one. Through the repeated landowners' decision-making, the ABM thus simulates a changing macro-level settlement pattern, in terms of number, type and location of the settlements. The paper focuses on the conceptual model in order to present the model entities and the dynamics underlying their interactions, and explain our choices and hypotheses.

Keywords: Agent-based modelling, Settlement dynamics, socio-natural systems, Roman Archaeology, Galia

Introduction

Since the early 90's, a group of French archaeologists has been developing a wide research program devoted to the analysis of long-term dynamics of the settlement system, in collaboration with geographers. Through successive projects1, they elaborated a series of indicators to describe and compare settlement's intensity, hierarchical structure and spatial distribution in various areas of Southern and Central France between the Iron Age and the Early Middle Age (Durand-Dastès et al. 1998; van der Leeuw, Favory & Fiches 2003).

Based on more than 2000 settlements identified in field surveys, these indicators were built on the same methodological basis in order to make the results comparable between different regions. They enabled to highlight regularities in the settlement's dynamics observed both in Southern and Central Gaul, as well as local specificities (Bertoncello et al. 2012; Ouriachi & Bertoncello 2015). For the beginning of the Roman period, two main patterns have been identified (Figure 1):

- from the 2nd c. BC to the 1st c. AD, a strong increase in the number of rural settlements caused a more concentrated spatial distribution of the settlements;
- During the 1st c. AD, the development of a new type of rural settlement - the Roman villa – led to a more hierarchized settlement structure;
- At the end of the 1st c. and during the 2nd c. AD, the number of settlements strongly declined in most areas, resulting in a more dispersed spatial distribution, while the hierarchical diversity of the settlements decreased.

In order to go beyond these observations regarding the state of the settlement system at different periods, it is necessary to investigate the processes that underlie its transformations through time. This interest in dynamics motivated the use of modelling to simulate the processes of creation, abandonment or maintenance of the rural settlements, in so far as these processes determine the quantitative, qualitative and spatial evolution of the settlement system. The Agent-Based Model we are presenting in this paper is in line with this perspective2: its purpose is to explore the respective role of environmental and human factors in the evolution of the settlement system during the Roman period. Agent-based modelling is particularly well suited to this goal as it allows to explore how interactions between the systems components at the micro-level generate new properties and structures of the system at the macro-level.

Our model is under development on the NetLogo platform (Wilensky 1999) and we will focus here on the conceptual model3. As usual in social sciences, the model components and their characteristics are based both on our knowledge (i.e. from archaeological and textual data) and on hypotheses that must be made explicit and that can be tested within this simulation framework. It is important to emphasize that our aim was, at this first stage of the modelling process, to set up the general framework of the model by defining its components and the main rules of their interactions underlying the system dynamics. Accordingly, this paper will present the entities of the model, the model dynamics and the expected outputs, before mentioning some future developments.

1 Mainly the two Archaeomedes projects (Archaeomedes I (1992-1994) « Understanding the Natural and Anthropogenic causes of soil degradation in the Mediterranean Basin », Program Environment of the European Commission DGXII; Archaeomedes II (1996-1999) « Policy relevant models of the natural and anthropogenic dynamics of degradation and desertification and their spatio-temporal manifestations », Program Environment of the European Commission DGXII, coordinated by Sander van der Leeuw, University of Cambridge), followed by the two Archaedyn projects (Archaedyn 1 (2005-2008) « Spatial dynamics of territories from Neolithic to Middle Ages », ACI « Spaces and Territories », French Ministry for Research and New Technologies, contract ET28; Archaedyn 2 (2009-2012), French National Agency of Research, contract ANR-08-BLAN-0157-01, coordinated by François Favory and Laure Nuninger, UMR 6249- USR 3124, Besancon, France).

2 This model is developed within the ModelAnSet project (« Modeling the role of socio-environmental interactions on Ancient Settlement Dynamics ») supported by UCAJEDI Complex Systems Academy of Excellence of University Côte d'Azur, Nice.

3 In order to ease the collaboration with the computer scientists in charge with the implementation of the ABM, we used the ODD (Overview, Design concepts, Details) protocol developed by Grimm et al. (2006; 2010) to describe the conceptual model.

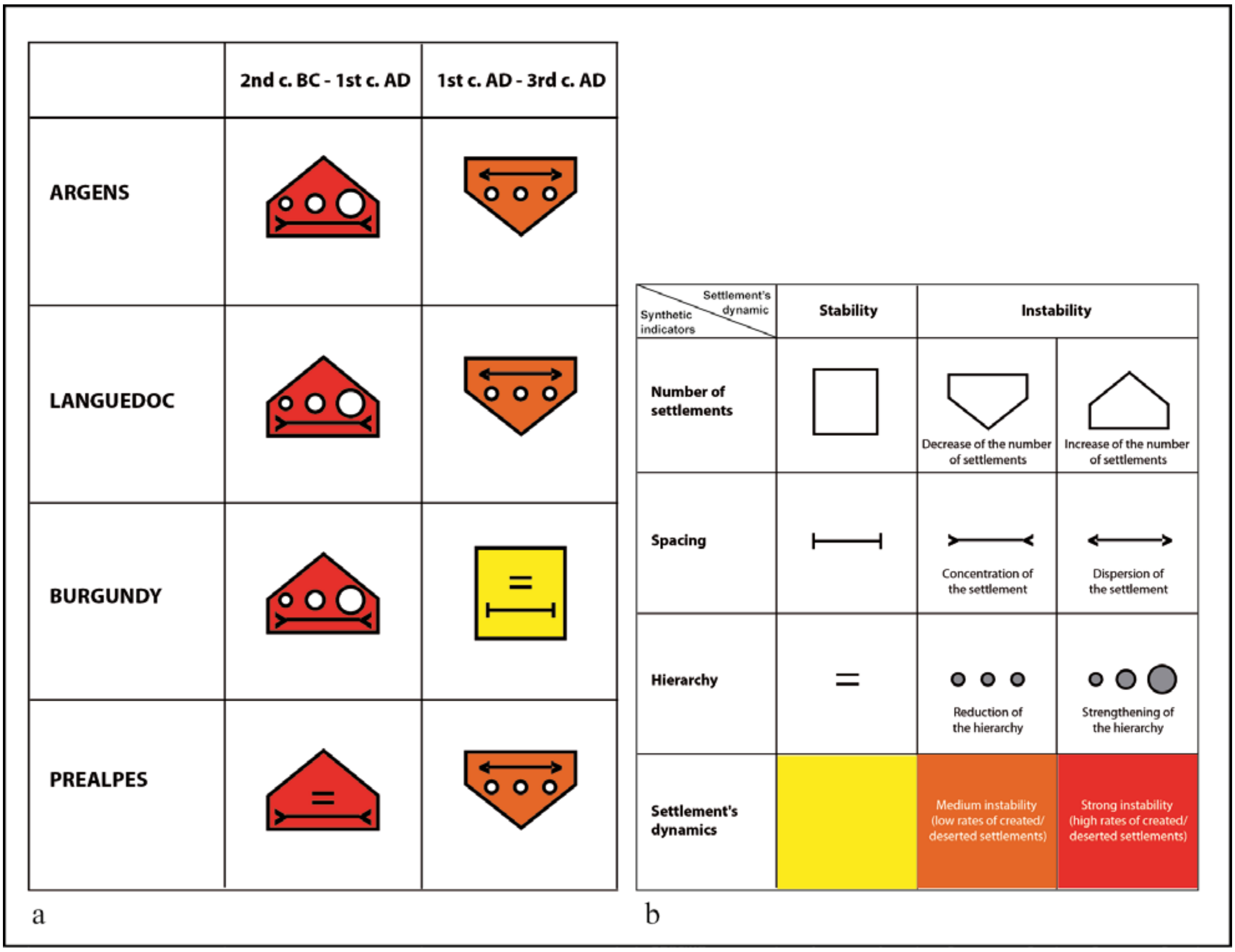

Figure 1. a: Synthetic representation of the settlement's dynamics in 4 French micro-regions between the 2nd c. BC and the 3rd c. AD according to the quantitative, spatial and hierarchical indicators developed within the Archaedyn project ; b: Legend of the symbols (from Ouriachi & Bertoncello 2015).

The Model Components: Agents and Spatial Entities

The dynamic of the system results from the creation, abandonment, or maintenance of the rural settlements. As the decision to create, abandon or maintain a rural estate mainly depends on its owner, we chose to simulate the behaviour of Gallo-Roman landowners regarding their agricultural holdings.

Although there was a great diversity of Gallo-Roman landowners, and as modelling imposes to simplify reality, we only consider three types of agents with different socio-economic status: the farmers, the big landowners, and within this group, the aristocrats, meaning magistrates who played a political role in the city. We decided that farmers could only possess one farm while big landowners and aristocrats could own several farms and villas, as evidenced by Latin texts. For the latter, theoretically, the number of properties held was set to a maximum of three for big landowners (including one villa) and six maximum for aristocrats (including at least three villas). In the model, this rule has to prevent one owner from possessing most of the lands in the territory of the city.

The size intervals assigned to each type of agricultural holding (farm/villa) were selected - as far as possible - based on historical and archaeological data. Indeed, this is a tricky historical problem: even when reliable data seem available (such as those given by the marble tablets of the cadastre of the Roman colony of Orange), it appears that the sizes mentioned (max. of 97 ha) are not those of the agricultural holdings, but those of public land allocated to farmers under land leases; moreover, among the successful tenderers, there are general farmers who want to

	Initial economic power	Maximum number and type of holdings	Spatial behaviour for the location of their holding(s)
Farmers	500 - 1000 (tokens)	1 (farm)	Restrained to their own holding
Big landowners	1000 - 5000 (tokens)	3 (including at least 1 villa)	Within a radius of 20 km from any of their holdings
Aristocrats	> 5000 (tokens)	6 (including at least 3 villas)	No spatial constraint (can create holdings anywhere); Attraction by the city capital: must have at least 1 of their holdings in a radius of 10 km from the capital

Table I: Attributes and behaviour rules of the agents.

take advantage of the "vectigal" (tax) collection but do not exploit the land (Favory 2012: 138-139). The assessment of the size of the Roman rural domain is mainly based on two types of data. The first ones are the size of the buildings and the storage or production capacity deduced from the agricultural installations. However, according to the authors, the same data produce very different results: for example, the domain of the villa of Settefinestre (Tuscany, Italy) varies from 25 to 125 ha, including 7.5 to 50 ha of vines (Compatangelo 1995: 46). In other cases, the surrounding landscape (concept of "natural region" based on topographical boundaries) is taken into account to define the area of land associated with a villa. Mauné (2010) thus estimates the surface of the villa of Quintus Iulius Pri(...) at Aspiran (Hérault, France) at 350 or 450 ha (Mauné et al. 2010: 113). Congès & Lecacheur (1994) evaluate the domain of the Pardigon villa (Var, France) at 80-100 ha with the first method (cellar storage capacity), and at 300 ha with the second one or 90 ha if considering only the plain (Congès & Lecacheur 1994: 286). We cannot mention all the numerous studies of this kind but these elements allowed us to set the size thresholds for the villas between 50 and 500 ha, knowing that some domains can reach far bigger sizes: for example, in another context, the estates of the villas in Roman Brittany varied between 60 and 1300 ha (Compatangelo 1995: 64-65)[4]. Concerning the farms, the surfaces are clearly lower: thus, Buffat (2010) mentions 15 ha of vines for the two farms of Gasquinoy (near Béziers, France), and more generally, archaeological surveys give areas from 10 to 20 ha (Buffat 2010: 183). Ouzoulias (2006) estimates that a tenant had to cultivate 17 to 22 ha of land in a subsistence farming context, to guarantee the persistence of his exploitation (Ouzoulias 2006: 199-200). Thus, for the farms, the size interval for the agricultural surface was set between 10 and 50 ha.

In addition to the dimensions of the domains, it is necessary to determine the behaviour of the landowners regarding each of their agricultural holding(s). We selected five actions: they can maintain their holding without change, enlarge or improve it, abandon it or create a new one. Their decision depends on their socio-economic status and the profit they derive from each holding or expect to derive if they create a new one. The socio-economic status of the landowners defines their initial economic power, the number and type of rural settlement they can own as well as their behaviour (tab. 1). We have some elements concerning the wealth of the aristocrats: we know that the census required from them is 400 000 sesterces under the Republic, and 1 million for the senators under the Principate, the census of the knights remaining unchanged. The magistrates had to pay the "summa honoraria/legitima" upon entering their public office. This sum varied according to the size of the city (for example 2000 sesterces in the colony of Urso for the "duumviri" and the "aediles", but 38000 sesterces in Carthage); nevertheless, it is obvious that magistrates were wealthy men. Regarding the farmers' income, ancient sources are even more scarce and it probably varied a lot from an area to another and according to the origin of the farmer (in our case: Gaul or Roman). We can get some clues from the case of the veterans of the Roman legions: from the information provided by Roman historians

4 We must also bear in mind that the "fundus" is an accounting unit that must be distinguished from the production unit. A fundus may comprise several production units (Compatangelo 1995: 52).

and biographers (especially Suetonius and Tacitus), F. Gayet calculated that the capital available for a veteran after his demobilization might amount to a minimum of 16 500 sesterces during the Augustan period, and between 10 500 and 12 000 sesterces minimum from Caligula to the Antonine period (Gayet, oral information).

It is very difficult to define values of general scope from figures so variable and specific to particular cases. Thus the ranges of values we chose for the initial economic power of each type of landowners are largely arbitrary and relative, in a ratio of 1 to 10 or more between the less wealthy farmer and any aristocrat (tab. 1). Allowing to change and « play » with these parameters is one of the interest of modelling to test and refine our hypotheses.

Things are getting even trickier when it comes to defining the landowners' behaviour. Regarding their economic behaviour, we consider that landowners demonstrate a certain rationality[5]. Indeed, in the model, the landowners decide what to do with each of their agricultural holdings according to the profit they derive from it or expect to derive if they create a new one.

This profit is related firstly to the production capacity of the holding, which depends on its environmental context. At this first stage of the model development, five very stylized types of environmental units were selected: alluvial plain, foothills, plateaux, sedimentary basins, hillslopes; each one is credited with a productive potential. The profit also takes into account the cost of transporting the goods to the nearest marketplace, i.e. the agglomerations. In the model, two types of agglomeration were distinguished to account for historical reality: one city capital and three smaller towns, with no administrative role (the so-called "secondary agglomerations").

The model was instantiated in a specific spatio-chronological context which is the territory of the Roman colony of Forum Iulii, the actual Fréjus in South-East of France, where archaeological and palaeoenvironmental studies have been conducted for over 20 years (Bertoncello 1999; Bertoncello et al. 2012; Bertoncello et al. 2014). This instantiation helped calibrating some model parameters (such as, for example, the relative proportions of towns, villas and farms in the settlement system) and will also allow to place the simulation in a realistic environment, based on the actual landscape of this area, although it is not fully implemented yet in the ABM.

The model also aims to integrate the impacts of two factors external to the settlement system on the production capacity of the rural holdings. The first one is the macro-economic context within the Roman Empire, which might have influenced the economic power of the landowners, for example through the fluctuations of the taxation and the state of the market. This economic factor has not been implemented yet in the model. The second element is the climate, which has an impact on land fertility. For the moment, climate change is simulated in a very coarse manner by randomly increasing or decreasing the landscape units' fertility, but it is planned to combine the ABM with a palaeoclimatic model.

The Model Dynamics (Figure 2)

At each iteration, the landowners' decision-making regarding each of their holdings depends on the combination of the evolution of their economic power and the profit derived from this particular farm/villa. The economic power of the landowners is not considered in its absolute value but in terms of evolution: at each iteration, their revenue (drawn from all their holdings) can be equivalent, superior or inferior to their revenue at the previous iteration. There are many intervening factors in the profit produced by an agricultural holding: the type and size of the domain, the amount of workforce, the size and efficiency of the agricultural equipment, the type of agricultural productions, the environmental conditions, etc. Due to the complex interactions between these elements, estimating the profit derived from each agricultural holding would require developing a specific model dedicated to this goal. This is envisioned as a medium-term perspective but at this stage, we accepted to use very rough estimators for the profit produced by each villa or farm in the model, in order to focus on the model structure. Thus in the model, the profit derived from each holding at each iteration can be "high" or "low" with respect to a theoretical average value fixed at 600 (tokens) for the farms and 6000 (tokens) for the villas. This value is the average between the minimal and maximal

5 Concerning the debate on rationality in Ancient economy, see for example Andreau et al. 2004.

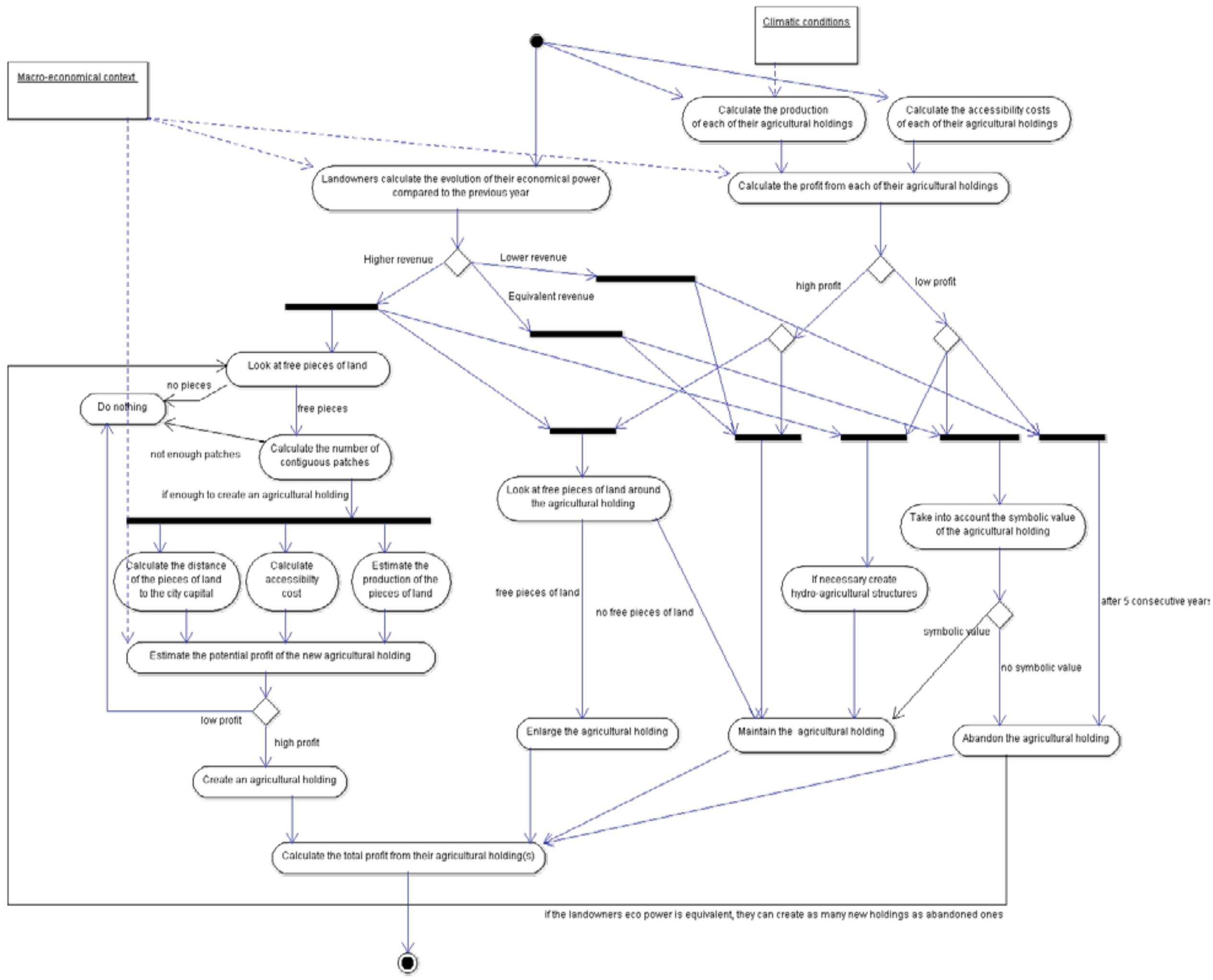

Figure 2. Flowchart of the model dynamics using the UML formalism.

profit values possible for each type of holdings (farm/villa) which depend on their size (i.e.: 10 to 50 ha for a farm and 50 to 500 ha for a villa) and on their production capacity, related to their environmental context (see above).

Table II shows the range of actions that can be performed by the landowners according to the evolution of their economic power and the profit derived from each holding. In the simplest case, when the landowner's revenue is lower than his previous one and the profit from his holding is high, he will maintain it without change. On the contrary, if the profit is low, he will abandon this farm or villa, but only after five consecutive years of low profit. This delay was introduced to take into account the variability of the agricultural production from one year to another and to avoid too much instability of the system; the five-years timescale is one of the parameters to be tested.

As farmers cannot own more than one farm, new agricultural holdings can only be created by big landowners and aristocrats, when their revenue is superior or equivalent. In this last case the landowners can only create new holding(s) if they abandon the same number of holding(s). Sufficient contiguous patches of land must be available to create a new estate, within the size intervals defined for farms and villas. According to their socio-economic status, landowners were assigned different spatial behaviour (Table I). As they can only improve or enlarge their existing farm, the farmers' range of action is limited to their holding. The aristocrats can create settlements anywhere but they are specifically attracted by the city-capital, as it is the place where they exercise their political functions. Indeed the Roman magistrates had to reside in the city-capital during their annual office, but they were also required to have at least one property in the territory, in order to guarantee

Landowner's economic power (t+1)	Profit derived from each agricultural holding		Possibility of creating new holdings (only for big landowners and aristocrats)
	High profit (Farm: > 600 tokens; Villa: > 6000 tokens)	Low profit (Farm: < 600 tokens; Villa: < 6000 tokens)	
Equivalent (=)	Maintain	Maintain	No
		Abandon	Yes
Higher (>)	Enlarge or Maintain	Improve or Maintain	Yes
Lower (<)	Maintain	Abandon	No

Table II: The actions performed by the landowners according to the evolution of their economic power and the profit derived from each agricultural holding.

their ability to assume their public responsibilities (see Berrendonner 2005: 83 who quotes the Law of Taranto which gives this information). Therefore, in the model, the aristocrats must have at least one holding in a radius of 10 km from the capital: according to ethnological studies, this distance corresponds to a two-hour walk. When they want to create a new holding, the patches of land located within this 10 km radius are granted an extra attractiveness value. In order to simulate various spatial behaviours, we hypothesize that the big landowners have a more « local » range of action than the aristocrats: they can only create new holdings within a radius of 20 km from any of their existing estates.

When the landowners' revenue is superior to the previous one, they can choose to maintain their settlement without change, enlarge it or improve it. By improvements, we mean various hydro-agricultural structures such as irrigation or drainage ditches, land terraces, stone clearance, etc., which can be created to improve the production of the land. This generates feedbacks between agents' behaviour and the properties of their environment, as they can improve land productivity. If such an "improved" domain comes to be abandoned, the presence of these hydro-agricultural structures is considered as an advantage to create a new agricultural holding on these lands, as they reduce the initial investment necessary to exploit them. In the model this is expressed by a higher value of attractiveness given to these patches.

Another feedback loop is introduced in the model by degrading land productivity after five years of consecutive exploitation.

Beside the economic value of the agricultural holding, its symbolic value is also taken into account. This refers to the attachment of some landowners to one specific settlement. We have mentioned the attractiveness of the city-capital for the aristocrats. Ancient texts and epigraphical documents also suggest that the owners attached particular importance to the estate where the family grave was located (see the example of the funerary monument of the Domitii family, located at Rognes, 15 km from the city-capital Aquae Sextiae /Aix-en-Provence, whose members belonged to the municipal aristocracy of the colony: Burnand 1975). In the model, this symbolic value will push the landowners to keep their holding even if its profit is low.

Expected Outputs

According to these processes, the repeated landowners' decision-making produces a changing macro-level settlement pattern, in terms of number, type and location of the settlements (Figure 3).

In order to explore the respective role of the chosen environmental (i.e. fertility of the various simulated environmental units, climatic conditions) and social (economic power and symbolic behaviour of the landowners, distance to the nearest town, macro-economic context) factors in the evolution of the settlement pattern and dynamics, various scenarios will be tested. The basic ones will be to run the model first without any climatic nor macro-economic variations, then to introduce climatic change or economic fluctuations, then both of them.

This raises the tricky question of estimating the validity of the various simulated scenarios. One way to do this in our case is to compare the simulated out-

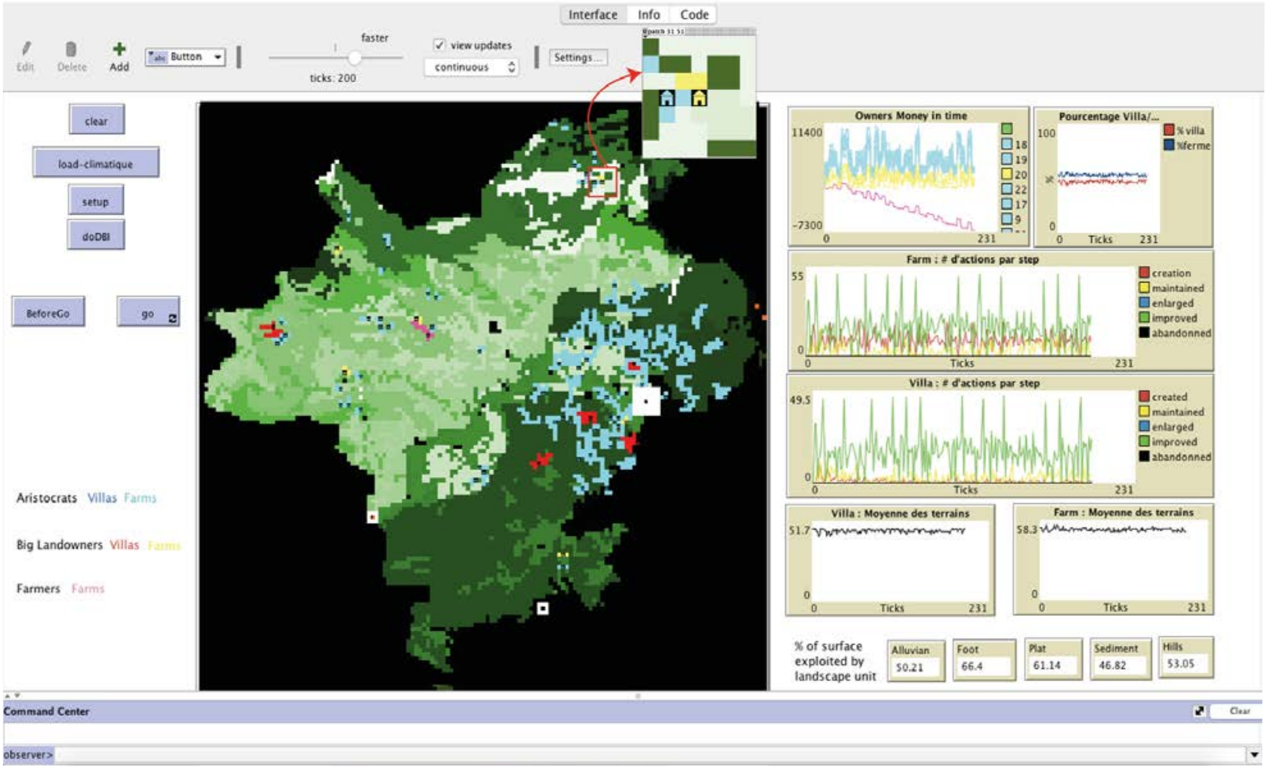

Figure 3. Screenshot of a simulation of the model on the NetLogo Platform, with a zoom on some patches.

puts with the archaeological records. This implies to produce outputs which are comparable to the quantitative, spatial and hierarchical indicators available to describe the settlement pattern and dynamics in the area of Fréjus during the Roman period (see Figure 1 above and Bertoncello et al. 2012; Ouriachi & Bertoncello 2015). The model will thus calculate, at each iteration, the proportion of villas and farms per type of landowner and per type of landscape units; the proportion of settlement maintained, enlarged, improved, abandoned or created; the minimum, average and maximum size of the estate for each type of settlement by type of owner; the minimum, average and maximum distance of each type of settlement by type of owner to the city capital and to the closest smaller town, etc.. In order to compare them to empirical data, these values will be compiled for a chosen number of iterations supposed to correspond to an archaeologically relevant period of time. It is obvious though that a good match between the simulated outputs and empirical data is not sufficient to draw firm conclusions on the causalities involved in the settlement dynamics. But this can help us to select which ones of our hypotheses are the most plausible. In that sense, modelling is a tool to think. It provides a testing of an hypothesis of process rather than a proof of the existence of process (« c'est une mise à l'épreuve plus qu'une preuve » : Tannier et al. 2017, 406).

Concluding Remarks and Perspectives

A first version of the ABM has been implemented and is now in the testing phase. Besides the unavoidable and necessary adjustments of the model, we would like to mention further developments that are envisioned in the near future. The first one concerns the ABM itself and more specifically the agents' behaviour. For the moment, the actions of the landowners are defined by fixed rules: according to the combination of these rules they react in one way or another. In opposition to these « reactive agents », the integration of « cognitive agents » in the model is currently tested in order to better take into account the complexity of human behaviour. The BDI model (Beliefs, Desires and Intentions: Bratman 1987) allows to assign agent beliefs about itself (for example in our case, its economic power) and its environment (estimation of lands' fertility), as well as desires (for example, creating a villa close to the city-capital), which will determine what actions the agent will initiate to reach its goal. Possibility Theory (Dubois & Prade 1988) is used to weight and prioritize the various desire generation rules, allowing to better account of the gradual nature of reasoning and deliberations of a cognitive agent in a context of uncertainty (da Costa Pereira & Tettamanzi 2010). Using such cognitive agents in our model opens interesting perspectives to integrate more nuanced perceptions of land productivity, of the impact of hydro-agricultural structures, of the macro-economic context, etc.The two other main developments planned for the model relate 1) to past climate and climatic changes, and 2) to the functioning of Ancient agrosystems. Each of these items requires a model per se, and the issue is thus to couple our ABM with both a palaeoclimatic and an agrosystemic models. This is the goal of the RDMed project which started in September 2018.[6] Based on the previous work done by the team of Joël Guiot at University Aix-Marseille, this project aims to simulate the response of Ancient societies to climatic change by developing an integrated model coupling our Agent-Based Model, an agroecosystemic model for agricultural production (adapted from the LPJmL model to Ancient agriculture: Contreras et al. 2019), an erosion model to simulate the effect of human activities on the landscape, and a palaeoclimatic model combining modern and palaeoclimatological data using a statistical downscaling technique to provide the appropriate temporal and spatial resolutions (Contreras et al. 2018). The prototype of the ABM we presented in this paper is thus a small preliminary brick in a more ambitious and long term project.

6 The RDMed (« Resilience and adaptation to Droughts and extreme climate events in the MEDiterranean: lessons learnt from past on a 1.5°C or more warmer world") project is directed by Joël Guiot (CEREGE, Aix-en-Provence) and supported by AMidex – Aix-Marseille University.

Reference

Andreau, J, France, J, Pittia, S 2004 *Mentalités et choix économiques des Romains.* Bordeaux: Ausonius Scripta Antiqua 7.

Berrendonner, C 2005 Les patrimoines fonciers des sénateurs de l'Italie républicaine: l'apport des sources épigraphiques. *Cahiers du Centre Gustave Glotz*, 16: 79-99. DOI: https://doi.org/10.3406/ccgg.2005.882

Bertoncello, F, 1999 *Le peuplement de la basse vallée de l'Argens et de ses marges (Var) de la fin de l'Age du Fer à la fin de l'Antiquité.* Unpublished thesis (PhD), University of Provence I, Aix-en-Provence.

Bertoncello, F, Devillers, B, Bonnet, S, Guillon, S, Bouby, L, Delhon, C 2014 Mobilité des paysages littoraux et peuplement dans la basse vallée de l'Argens (Var, France) au cours de l'Holocène. *Quaternaire*, 25 (1): 23-44. DOI: 10.4000/quaternaire.6893

Bertoncello, F, Fovet, E, Gandini, C, Trément, F, Nuninger, L 2012 The spatio-temporal dynamics of settlement patterns from 800 BC to 800 AD in Central and Southern Gaul: models for an interregional comparison over the long term (Chapitre 3). In: Gandini, C, Favory, F, Nuninger, L (eds.) *Settlement Patterns, Production and Trades from the Neolithic to the Middle Ages. ARCHAEDYN, Seven Millennia of Territorial Dynamics, Final Conference, Dijon, 23-25 june 2008. British Archaeological Reports Int. Series*, 237. pp. 51-64.

Bratman, M 1987 *Intentions, Plans, and Practical Reason.* Cambridge: Harvard University Press.

Buffat, L 2010 Fermes et villas en Gaule Narbonnaise. In: Ouzoulias, P and Tranoy, L (eds.) *Comment les Gaules devinrent romaines*. Paris: La Découverte. pp. 177-188.

Burnand, Y 1975 Domitii Aquenses. *Une famille de chevaliers romains de la région d'Aix-en-Provence. Mausolée et domaine. Revue archéologique de Narbonnaise*, suppl. 5. Paris: De Boccard.

Compatangelo, R 1995 Prospection archéologique et domaine: modèles historiques et réalités de terrain. In: *Du Latifundium au Latifondo. Un héritage de Rome, une création médiévale ou moderne?* Actes de la Table ronde internationale du CNRS organisée à l'Université Michel de Montaigne - Bordeaux III, les 17 - 19 décembre 1992. Paris: Publication du centre Pierre Paris. pp. 45-65.

Congès, G and Lecacheur, P 1994 Exploitation et domaine sur la côte varoise à l'époque romaine : exemple de la plaine de Pardigon (Cavalaire, Croix-Valmer, Var). In: Favory, F and Fiches, J-L (eds.) *Les campagnes de la France méditerranéenne dans l'Antiquité et le haut Moyen Age.* Etudes microrégionales. Paris: Éditions de la Maison des Sciences de l'Homme. pp. 279-288.

Contreras, D, Guiot, J, Suarez, R, Kirman, A 2018 Reaching the human scale: a spatial and temporal downscaling approach to the archaeological implications of paleoclimate data. *Journal of Archaeological Science*, 93: 54-67. https://doi.org/10.1016/j.jas.2018.02.013

Contreras, D, Bondeau, A, Guiot, J, Kirman, A, Hiriart, E, Bernard, L, Suarez, R, Fader, M 2019 From palaeoclimate variables to prehistoric agriculture: Using a process-based agroecosystem model to simulate the impacts of Holocene climate change on potential agricultural productivity in Provence, France. *Quaternary International*, 501: 303-316. https://doi.org/10.1016/j.quaint.2018.02.019

Da Costa Pereira, C, Tettamanzi, A 2010 An Integrated Possibilistic Framework for Goal Generation in Cognitive Agents. In: van der Hoek, W, Kaminka, G, Lésperance, Y, Luck, M, Sen, S (eds). *Proc. of the 9th International conference on autonomous agents and multiagent systems* (AAMAS 2010). Toronto, pp. 1239–1246.

Dubois, D, Prade, H 1988 *Possibility Theory*. New York: Plenum Press.

Durand-Dastès, F, Favory, F, Fiches, J-L, Mathian, H, Pumain, D, Raynaud, C, Sanders, L, Van der Leeuw, S 1998 *Des oppida aux métropoles. Archéologues et géographes en vallée du Rhône*. Paris: Economica.

Favory, F (dir.) 2012 *Le Tricastin romain : évolution d'un paysage centurié (Drôme, Vaucluse)*. Lyon: DARA.

Grimm, V, Berger, U, Bastiansen, F, Eliassen, S, Ginot, V, Giske, J, Goss-Custard, J, Grand, T, Heinz, S, Huse, G, Huth, A, Jepsen, JU, Jørgensen, C, Mooij, WM, Müller, B, Pe'er, G, Piou, C, Railsback, SF, Robbins, AM, Robbins, MM, Rossmanith, E, Rüger, N, Strand, E, Souissi, S, Stillman, RA, Vabø, R, Visser, U, DeAngelis, DL 2006 A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, 198: 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023

Grimm, V, Berger, U, DeAngelis, DL, Polhill, JG, Giske, J, Railsback, SF 2010 The ODD protocol: A review and first update. *Ecological Modelling*, 221: 2760–2768. https://doi.org/10.1016/j.ecolmodel.2010.08.019

Mauné, S, Durand, B, Carrato, Ch, Bourgaut, R 2010 La villa de Quintus Iulius Pri(…) à Aspiran (Hérault). Un centre domanial de Gaule Narbonnaise (Ier – Ve s. apr. J.-C.). *Pallas*, 84: 111-143. DOI: 10.4000/pallas.3383.

Ouriachi, M-J, Bertoncello, F 2015 An 'alphabet' to describe the spatio-temporal dynamics of settlement systems: a relevant representation of time? In. Giligny, F, Djindjian, F, Costa, L, Moscati, P, Robert, R (eds.) *CAA 2014 - 21st century Archaeology: Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* Oxford, Archaeopress, pp. 393-398.

Ouzoulias, P 2006 *L'économie agraire de la Gaule: aperçus historiographiques et perspectives archéologiques.* Unpublished thesis (PhD), University of Franche-Comté, Besançon.

Tannier, C, Franc, A, Ouriachi, M-J, Zadora-Rio E 2017 Entre modèles et récits, les transitions dans les systèmes de peuplement. In: Sanders L (ed.). *Peupler la terre. De la préhistoire à l'ère des métropoles.* Tours, Presses Universitaires François Rabelais, 2017, p. 387-407.

Van der Leeuw, S, Favory, F, Fiches, J-L 2003 *Archéologie et systèmes socio-environnementaux : études multiscalaires sur la vallée du Rhône dans le programme Archaeomedes.* Paris: CNRS éd. (CRA monographies, 27).

Wilensky, U 1999 *NetLogo. http://ccl.northwestern.edu/netlogo/*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

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James R. Allison
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Virtual Kinship Networks: Exploring Social Networks from an Agent-Based Model

James R. Allison
Department of Anthropology,
Brigham Young University
jallison@byu.edu

Abstract

This paper analyzes the structure of virtual kinship networks formed by an agent-based model that was originally designed to explore the relationships among kin networks, residence rules, settlement size, and the movement of exchange goods.Following simple rules, agents in the model are born, die, find mates, establish post-marital residence. Agents then exchange goods (which are conceptualized as pottery vessels) among close kin dispersed through a linear system of villages. Each run of the model produces a network that unites most agents, but each agent also has a personal network of close kin. Previous analysis of model output has focused on variation in the number of virtual pottery vessels obtained by agents, and on data averaged over large numbers of model runs, with only minimal analysis of the networks produced. But variation in network structure must underlie the variation in exchange success seen in the model runs. This paper focuses on the virtual networks produced by the model, including examining variation in measures of centrality and degree distribution, as well as variation in path length from one end of the system to the other. The data exploration reported here indicates that centrality is important, but centrality alone is not a good predictor of success in exchange. Agents who obtain large numbers of vessels typically are connected to producers directly or through one or two intermediate links, and also tend to have relatively high centrality in the network.

Keywords: agent-based modeling, exchange, social networks

Introduction

This paper explores the structure of virtual kinship networks formed by an agent-based model that was originally designed to investigate the relationships among kin networks, residence rules, settlement size, and the movement of exchange goods in a simulated exchange network. The model was inspired by archaeological ceramic distributions where contemporary and adjacent households acquired quite different amounts of imported ceramics. It is often difficult to get large enough samples that can be clearly associated with individual archaeological households, but wherever ceramic assemblages from individual households, or small groups of a few households, can be separated, it is common to find that the relative abundances of trade ware pottery vary much more than can be accounted for by sampling error (e.g., Allison 2019; Allison 2008; Ossa 2013; Watts and Ossa 2016).

Variation in the relative abundance of non-local ceramics may reflect differences in household wealth and status, although the variation occurs among households in small-scale farming societies where there is little evidence for strong differences in prestige or wealth. Access to goods from distant sources may be better for some households than others for other reasons, however. Specifically, several recent attempts to model exchange have emphasized the importance of small-world networks (e.g., Brughmans and Poblome 2016a; Brughmans and Poblome 2016b; Ibañez et al. 2015; Ortega et al. 2014). The model analyzed here was developed to test the intuition that, under certain conditions, exchange networks formed through kinship would tend to be small-world networks in which some individuals were more successful in acquiring exchange goods.

Previous analysis of the model results (Allison 2020) shows that it is generally true that trade along kinship lines results in large differences in how successful agents are in acquiring trade ware vessels, with the variation being largest when the size of settlement size is smallest. This variation in exchange success must be due to random variation in the size and specific composition of the virtual kin networks formed by the model, but the details of those networks have not previously been examined.

The purpose of this paper is to begin to examine the networks formed in the simulation and how individual's positions in those networks affect their success in acquiring vessels through exchange. These networks are not created to have any specific form, but rather they emerge through agents following simple rules of kinship, marriage and residence. Exchange is then channeled through kinship links. Because the networks emerge in part through stochastic effects, each run of the model creates a different network, which makes analysis complicated and generalizations difficult. To simplify, I will focus on a few questions. First, how does network topology vary with the size of settlements and overall population (which are correlated because the number of settlements is constant)? Specifically, are there differences in the distributions of degree centrality, betweenness centrality, or the path lengths between settlements as settlement size varies. For these broad questions about the structure of networks, I will use 50 runs of the model, ten each with initial settlement size population set to 100, 200, 300, 400, and 500 agents (the actual population of settlements varies stochastically as agents are born and die according to specific probabilistic rules).

A second set of questions focuses in on how centrality of agents or path length to ceramic producers affects success in acquiring vessels in exchange. If exchange success is in fact a result of agents being well-positioned in a small-world network, then path length to producers should be positively correlated with the number of vessels acquired, but network centrality should not be as important. For some analyses relevant to these question I use the full complement of 50 model runs, but I also will focus in on the specific kin networks of a few agents in two runs of the model, one with initial village size set to 100, the other with it set to 500.

Brief Description of the Model

The model is implemented in NetLogo 6.0 and is available for download at https://github.com/jallison7/kintrade-model. Allison (2020) describes the model more completely; here I present a brief summary to help readers make sense of the analyses that follow.

The model is inspired by the archaeological case studies described in Allison (2019; Allison 2008), but is not specifically based on any real world situation. It creates settlements ("villages") evenly spaced in a line from left to right (in NetLogo's "world" display)

Initial Village Size	Total No of Agents at End	Village Size at End	Degree Centrality		Betweenness * 100		Path Length	
		mean	mean	median	mean	median	mean	median
100	6116	76.5	5.6	3	0.8	0.006	2.9	3
200	13701	171.3	5.7	3	0.4	0.009	3.4	3
300	20256	253.2	5.6	3	0.3	0.010	3.5	3
400	28418	355.2	5.7	3	0.2	0.005	3.4	3
500	36004	450.1	5.6	3	0.2	0.004	3.8	4

Table I: Statistics from 50 total runs of the model

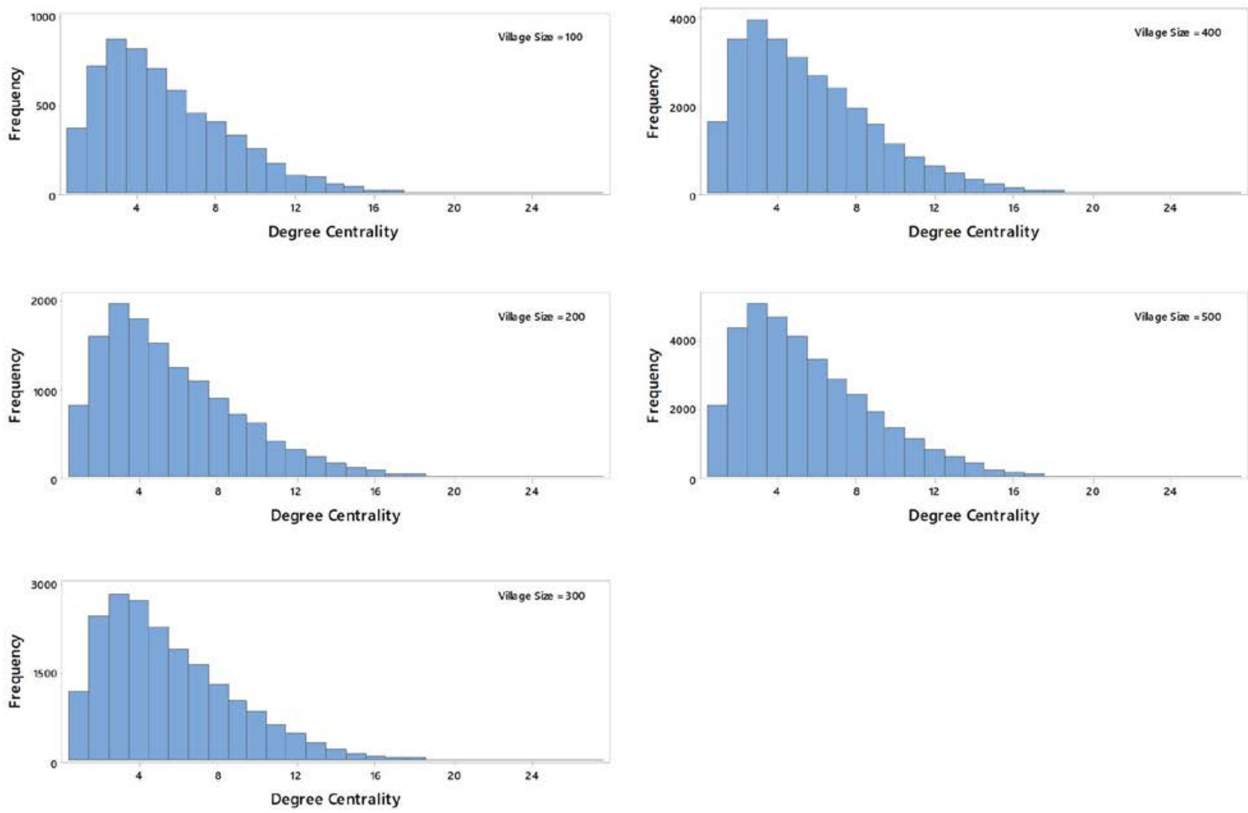

Figure 1. Degree distribution for networks created with different initial village sizes.

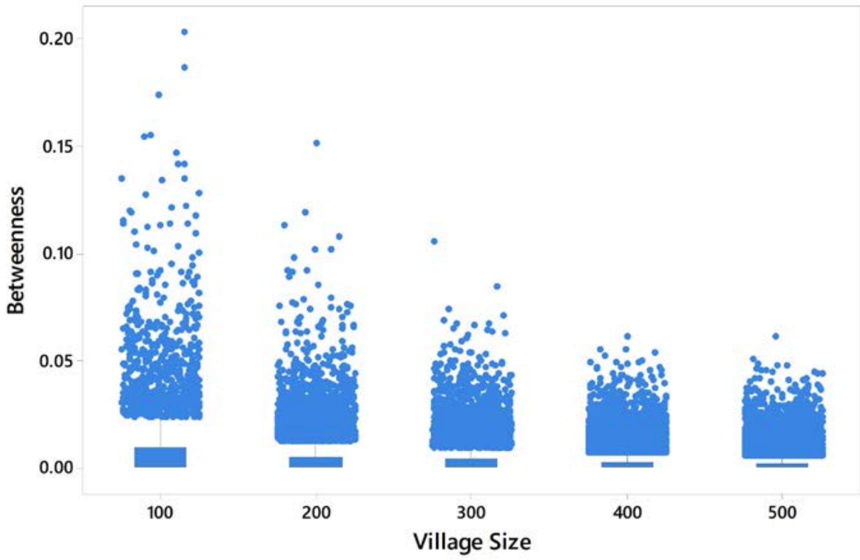

Figure 2. Box plots of betweenness for agents in the networks created by the model at different initial village sizes.

within an abstract, featureless landscape. The number of villages can vary, but all the runs of the model reported here use eight villages (the [otherwise arbitrary] choice to use a linear arrangement of eight villages is an homage to Wright and Zeder's [1977] pioneering model of exchange, which was one of the first agent-based models in archaeology). The villages are numbered left to right, and the two villages at the left side of the system (i.e., Villages 1 and 2) are defined as producing villages.

The initial mean population size of the villages is set before each run. The actual number of village residents is random; the model randomly chooses the number of male and female agents to create in each

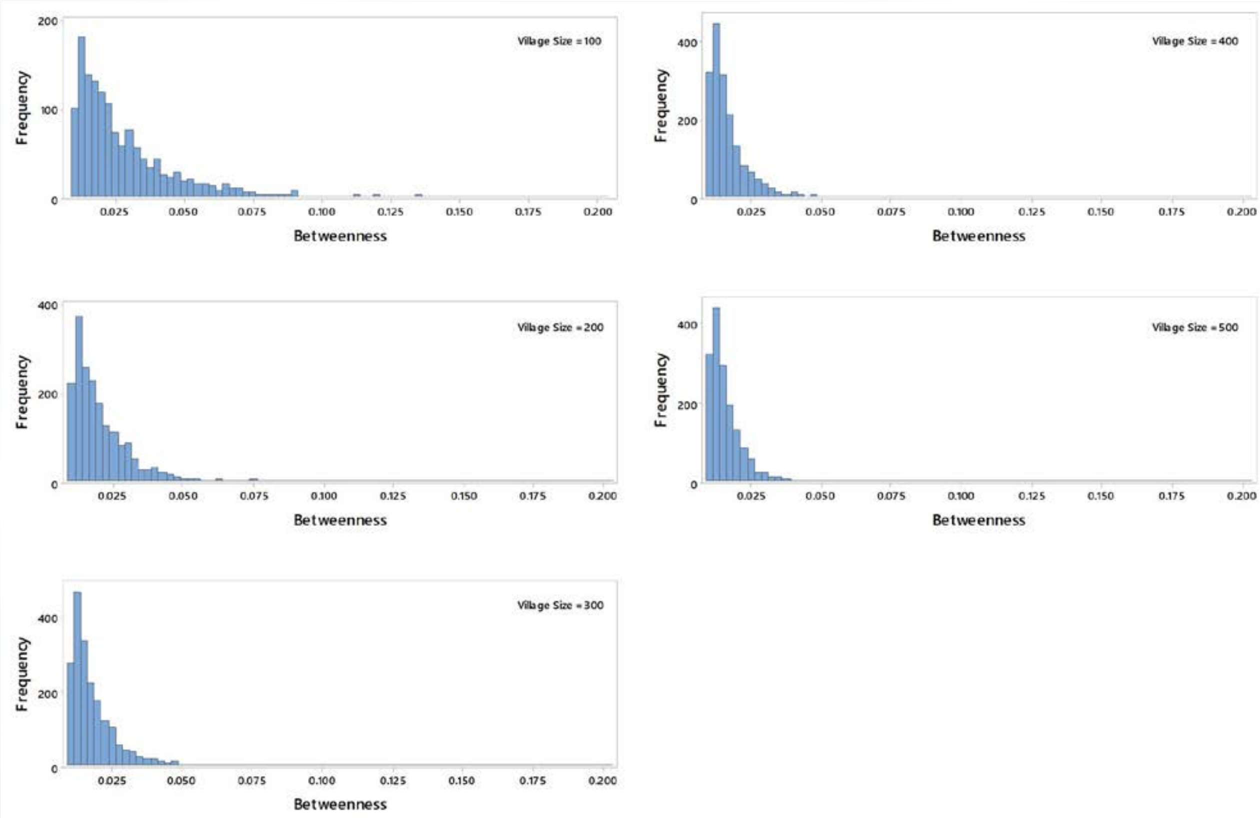

Figure 3. Histograms of normalized betweenness values for networks created at different village sizes, with betweenness values below 0.01 excluded.

village from a Poisson distribution (with a mean = ½ the mean initial village size). Agents in this initial group are randomly assigned ages, then seek spouses, with age restrictions. The system is matrilocal with a preference for endogamy (i.e., agents marry within their home village if possible); if no spouse is available in the home village, men move to their spouse's village. The simulation then runs for 100 years (each NetLogo "tick" is conceptually one year) while agents have children, marry, and die according to specific rules. The model links spouses, parents and children, and siblings. Agents are also linked directly to their spouses parents and siblings. After 100 years, the simulation will have created a network that indirectly links most or all of the agents in the model, and agents will have their own networks of first and second order links. But because birth, death, marriage, and reproduction are all subject to stochastic affects, some agents will be directly or closely connected to many other agents, while others have few close connections.

After the simulation has run for 100 years to allow the network to emerge, female agents in the producing village begin producing pots, and the pots are then traded, with all transactions occurring between directly linked individuals. Several variables in the model were held constant in the model runs reported here. These include the number of vessels produced annually by each producer (5), the number of vessels an individual must possess before they are willing to give one to a relative (2), and the number of vessels agents can acquire in a year before they stop trying to get more (5). The length of the period during which exchange takes place was also held constant (at 50 years), although it also is potentially variable. Agents continue to be born, age, marry, reproduce, and die throughout the period of exchange. Birth and death probabilities are also variable in the model but fixed in the runs reported here. The probability that any agent over the age of 16 will die in a given year was fixed at .05. Birth probability, or the probability that a female between the age of 16 and 40 will have a child in a given year was set at .017 (since agents under 16 cannot die in the model, this value really reflects the probability that a female agent will have a child that survives to adulthood rather than a raw birth rate).

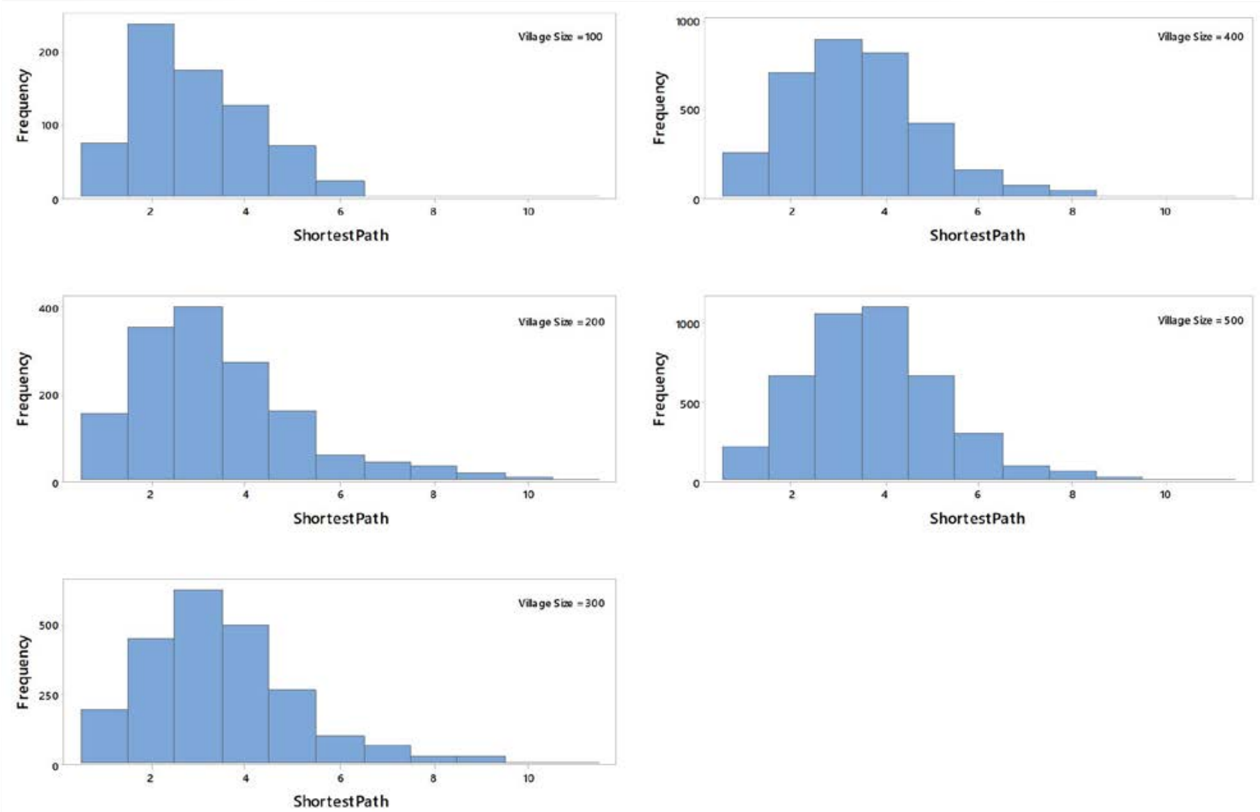

Figure 4. Distributions of shortest path lengths from Village 8 agents to agents in the producer villages (Villages 1 and 2).

These settings lead to relatively stable populations, although, as the first two columns of Table 1 show, population tends to decline slightly throughout the duration of the simulation. The actual sizes of villages vary somewhat, but by the end of the 150 year run, mean village population is about 87 percent of the initial village size.

Analysis, Part 1: The Effect of Settlement Size on Centrality and Path Length

Settlement size, which correlates to total population size, has almost no effect on the distribution of degree centrality. Agents have a mean of 5.6 or 5.7 direct links, regardless of the size of the total network, and the median is 5.0 for every village size setting (Table 1). The distributions of degree centrality are all skewed (Figure 1), with individual agents having more than 20 direct links, but the distributions are virtually identical regardless of settlement size.

Betweenness centrality varies more with initial settlement size, although the distributions are so skewed that it is difficult to graph them clearly. The boxplots in Figure 2 show that almost all the agents at every settlement size have very small betweenness values, but there are large numbers of outliers. Because of the large number of tiny values, it is difficult to scale histograms of the full distributions to show much except a large mode in each histogram for the bin that includes zero. Figure 3 excludes a total of 95,708 agents that have normalized betweenness centrality less than 0.01; excluding those values makes it much easier to see that the range of values is higher when the settlement (and total) populations are smaller. In other words, when populations are smaller, it is possible for some agents to be more central to the network than they can be when settlement size, and the size of the total network, are larger. This is reflected in the mean values for betweenness, which are always small but decrease steadily as settlement size increases, while the median values are much tinier, with fluctuations that are likely just due to sampling error.

Path lengths also vary with population size, although again the effects are subtle. Figure 4 shows the shortest paths for agents in Village 8 (furthest from the producers) to any agent in one of the two producing villages. At each village size, most agents

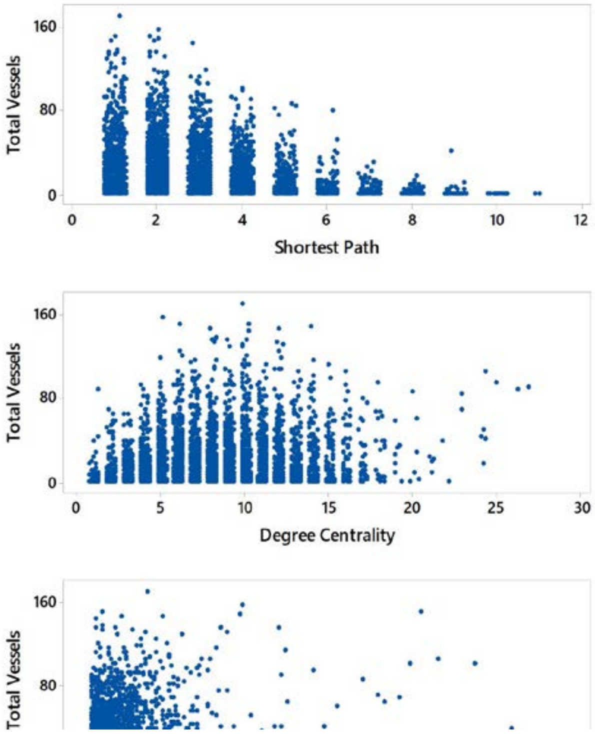

Figure 5. Plots of the relationship between total vessels acquired and path length, degree centrality, and betweenness for Village 8 agents across all 50 runs of the simulation.

in Village 8 are connected to someone in the producing village by four or fewer links, and the mdian is three for every village size except 500 (Table 1). The mean path length increases from 2.9 to 3.8, however, and 44 percent of the Village 8 agents are directly connected to someone in a producing village (i.e., path length = 1) when village size is 100, compared to only 21 percent when village size is set to 500.

In general, then, there are some slight differences in the characteristics of networks created by the simulation as population sizes increase. The degree distributions of the networks vary little with village size. At every population size, the simulation creates networks within which most agents have three or fewer direct links, but a few agents have many more. At every initial village size setting, most agents have similar, quite small values for betweenness, indicating that most agents are not very central to the network, although the range of values is larger when the network is smaller. Path lengths across the virtual landscape also vary with population size; when settlement size is small, the model creates networks in which many agents at the far end of the system (in Village 8) are linked to the producing village directly or with relatively few links. At larger population sizes, average path lengths increase, although a few Village 8 agents are still connected to producers directly.

Analysis, Part 2: Path Length, Centrality, and Success in Acquiring Vessels

Path length to the producing villages does have a large effect on the number of vessels acquired by agents. The upper graph in Figure 5 shows that relationship for all agents in Village 8, across all 50 runs of the simulation (a total of more than 12,000 agents). Total vessels, as shown in Figure 5, is the sum of vessels in possession of agents at the end of a simulation run, and vessels that they acquired earlier but gave away before the end of the run. Although the relationship is visually striking, the correlation is actually quite small (r2 = .09) because so many agents acquire only small numbers of vessels, even when they are connected to one of the producing villages through few links. This may mean there are confounding variables (age is one likely factor, since older individuals have more opportunities to acquire vessels). But, clearly, some individuals with short paths to producing villages are able to acquire large numbers of vessels, which individuals with longer path lengths are not able to do so.

Neither degree centrality nor betweenness seems to have a strong or consistent relationship with pots acquired, however (Figure 5), except that agents with high centrality scores tend to have at least moderate numbers of vessels. But the individuals with the largest numbers of vessels have low to moderate centrality in the network. The correlations with total vessels are actually higher than for path length (.16 for degree centrality and .22 for betweenness) but are still low.

The overall relationships among these variables are suggestive but ambiguous. Having a short path to a producing village seems to be necessary, but not sufficient, for agents to acquire large numbers of vessels. And agents that are highly central in the network almost always have some success at acquiring vessels. But the patterns shown in Figure 5 indicate that other factors must be important as well.

Figure 6 shows the relationship between total vessels and path length and between degree centrality and betweenness for Village 8 residents in two runs of the simulation. In the top row of the figure, the ini-

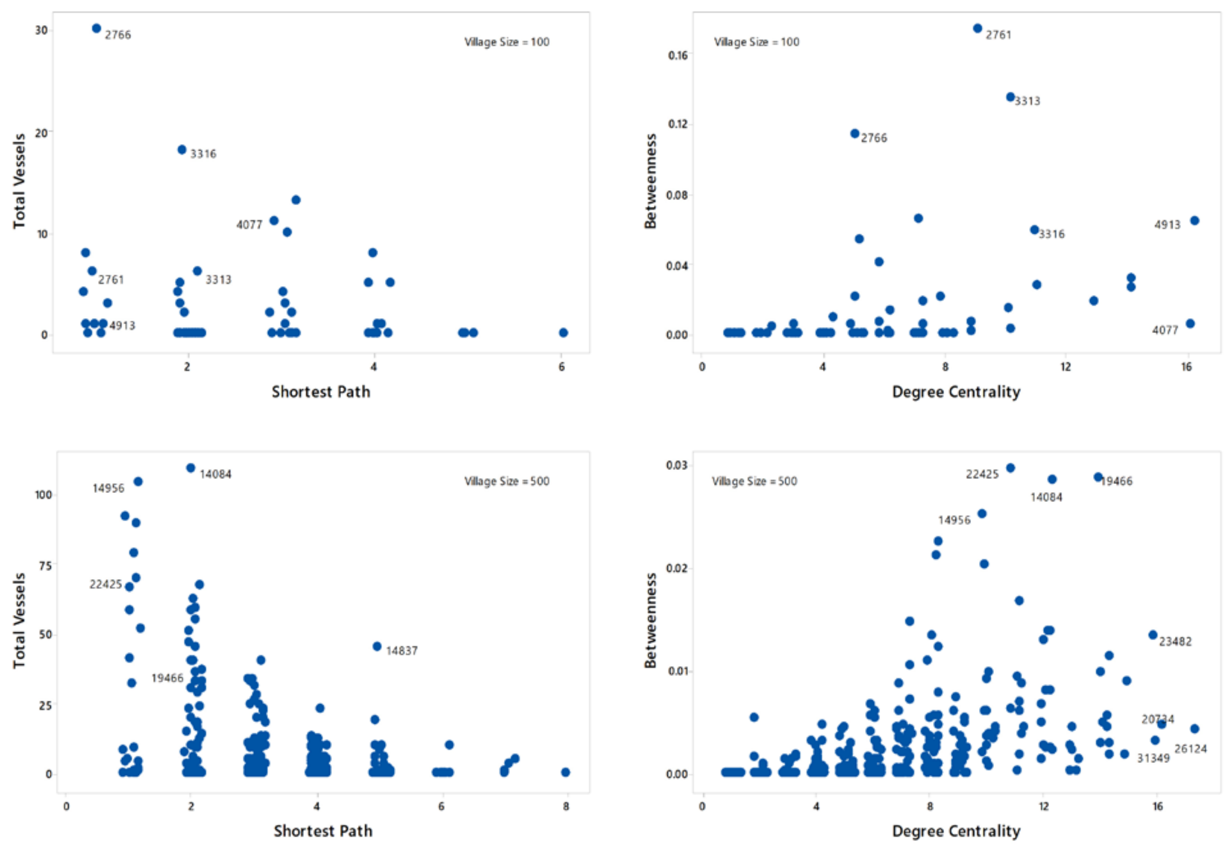

Figure 6. Plots of the relationships between shortest path and total vessels and between degree centrality and betweenness, for Village 8 agents in two runs of the simulation. The top row shows the relationships for a run with an initial village size of 100. The bottom row is for one run with initial village size set to 500.

tial village size was 100, in the bottom row it was 500. Aside from the differences in the number of data points resulting from the different population sizes, the graphs from the two runs are similar. The agents who acquire the most vessels always have direct connections to a producing village or a relatively short path, and agents with relatively high betweenness values always have moderate to high degree centrality, although the reverse is less true. Many agents with relatively high degree centrality have low betweenness values.

A few individual agents are labeled in Figure 6 that have large numbers of vessels acquired, high centrality, or both. A closer examination of the details of those agents and their closest connections provides insight into the nature of the networks that emerge in the simulation and how agents' situations within the networks affect their success in obtaining vessels through exchange.

In the top half of Figure 6, showing Village 8 residents from one run of the model with initial village size set to 100, most of the labeled agents are closely connected to each other and have overlapping networks of close connections (Figure 7).

Agent 2766, a 59 year-old male who has acquired more vessels than any other Village 8 resident, was born in Village 7 but married into Village 8. Agent 2761 is his spouse, through whom he connects to a large group of Village 8 agents (plus others). They both have direct connections to agents in the producing villages. Agent 2766 is directly connected to Agent 4404, a female who lives in Village 1. At the end of the simulation Agent 2766 only owned 5 vessels (2 of which were produced by 4404), but he had traded away 25 others. He has relatively high betweenness (0.11) and moderate degree centrality 5, as shown in the upper right graph in Figure 7.

Agent 2761, 2766's spouse, is also 59 years old. At the end of the simulation she only owned one vessel and had traded away five. She stands out as having the highest betweenness of any Village 8 resident (0.17) and relatively high degree centrality (9). She is

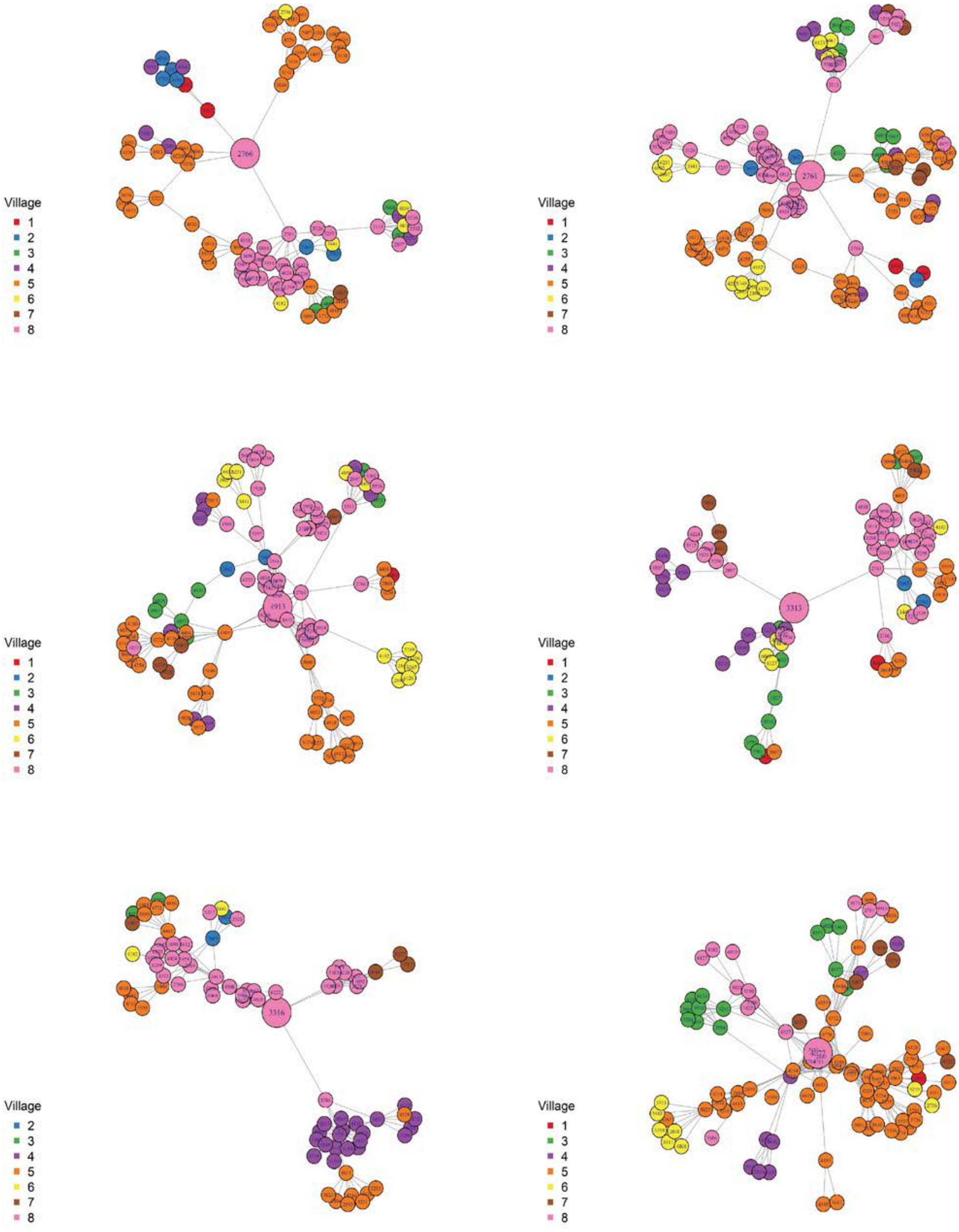

Figure 7. Network graphs of the closest connections for specific agents labeled in the upper half of Figure 6.

directly connected to Agent 3665, a male who lives in Village 2.

4913 is a 24 year-old male, the son of agent 2761 from a previous marriage (his father is deceased). He

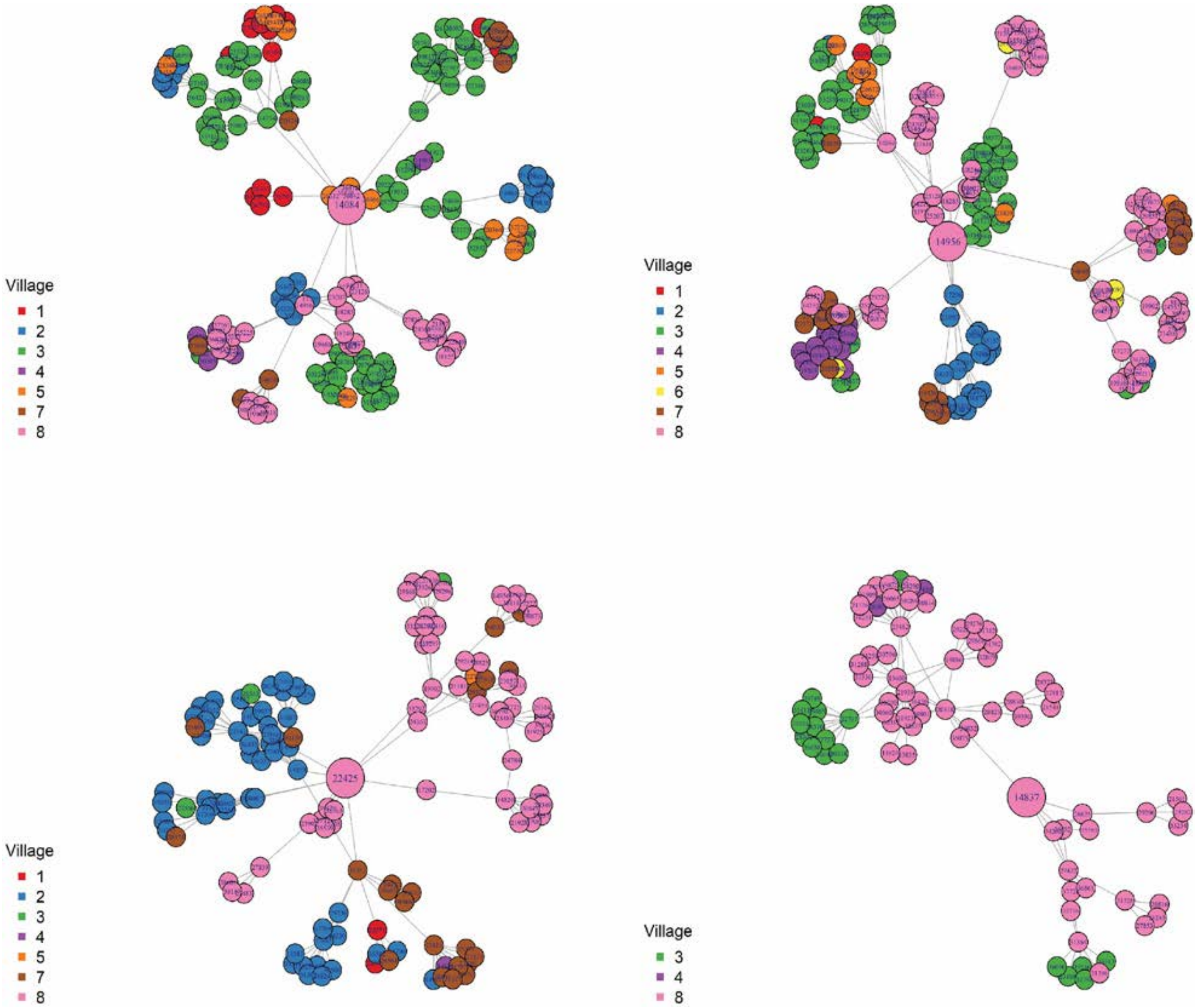

Figure 8. Network graphs of the closest connections for four of the agents labeled in the lower half of Figure 6.

is highly central in the network, at least in terms of degree centrality (16), and he shares the direct connection with his mother to Agent 3665 in Village 2. This probably means that means that 2761's deceased spouse, and father of 4913 married into Village 8 from Village 2, although information about agents who die before the end of the model run is not recorded, so the specifics of that connection cannot be verified. Despite Agent 4913's high centrality and direct connection to a producing village, he has only acquired one vessel. That may be due in part to his relatively young age.

Agent 3313 is a 48 year old female, who has high betweenness and degree centrality (10). Her close connections overlap substantially with Agent 2761, who is her sister, and she connects indirectly to Agent 3665 in Village 2 through her sister. At the end of the simulation she only owned 1 vessel, but had traded away 5.

3316 is also a 48 year old female, who owns only one vessel but has acquired and traded away 17. Her closest connection is also to Agent 3665, through Agent 4913 who is married to her daughter. It is not clear why she was more successful in obtaining vessels than other agents with largely overlapping networks and equally short or shorter paths to the producers.

Most of the Village 8 agents in this run of the simulation who have high centrality or large numbers of vessels are thus closely connected to each other. Agent 4077 is an exception. He is a 37 year old male who was born in Village 5. At the end of the simulation he owned six vessels and had traded away five others. He is tied for the highest degree centrality in

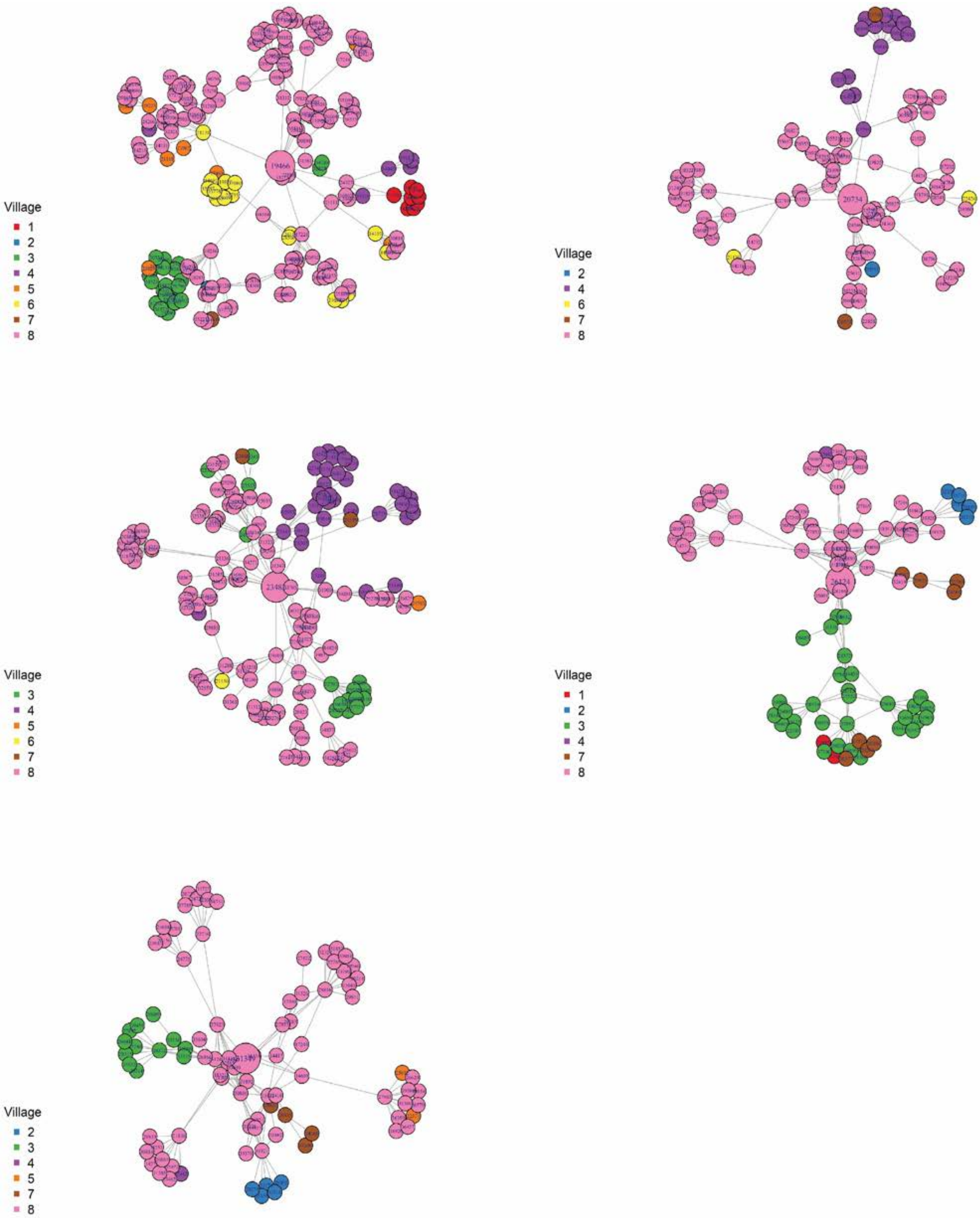

Figure 9. Network graphs of the closest connections for five agents labeled in the lower half of Figure 6.

the village (16), but has very low betweenness (.006), and is two links away from the producing village. His closest connection in a producing village is Agent 5097, a male who was born in Village 6 but married into Village 1. The connection goes through two Village 5 residents, Agent 5094 who is his sister, and Agent 5095, sister in-law to 5094, who is married to Agent 4863, 5097's brother. Again it is not clear why

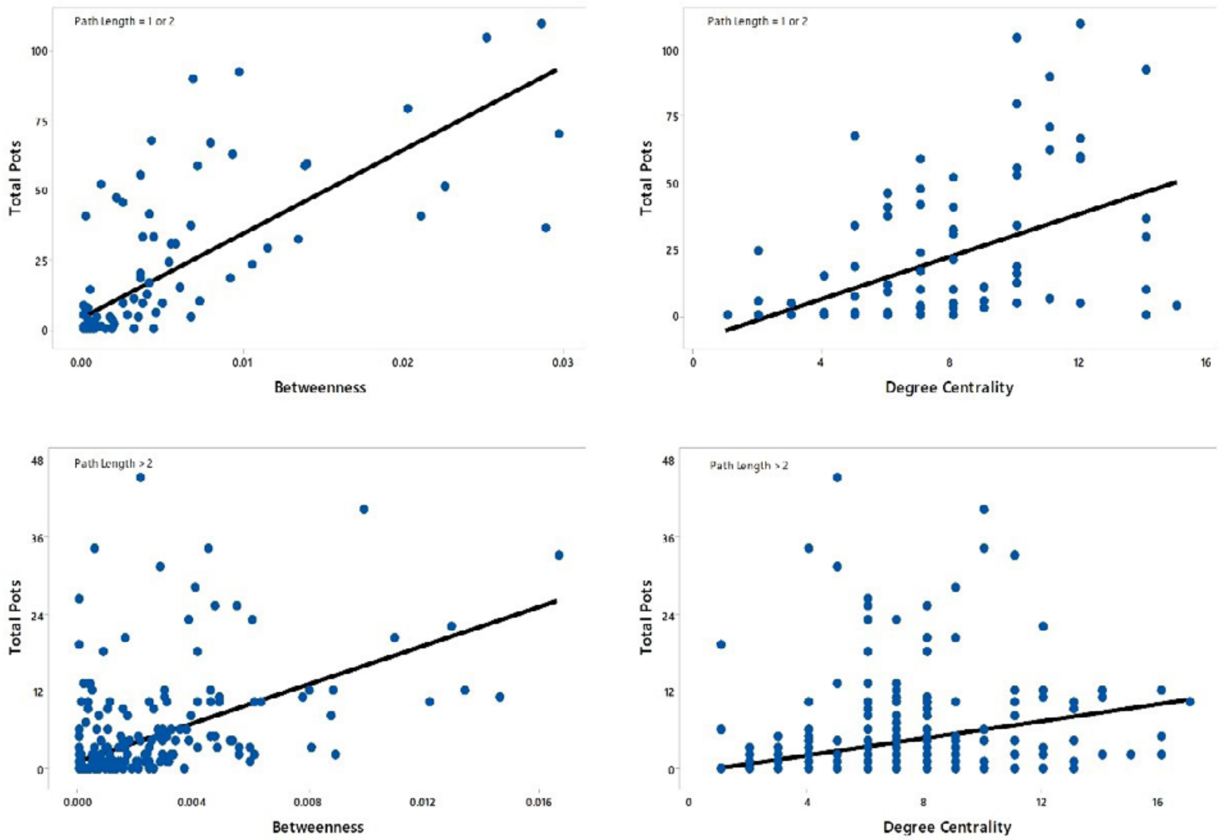

Figure 10. Graphs showing the relationships between centrality measures and total pots acquired for Village 8 agents from one run of the simulation with initial village size set to 500. The upper row graphs the relationships for agents with short path lengths to producer villages; the bottom row shows the weaker relationship for agents with longer path lengths.

Agent 4077 was relatively successful at obtaining vessels, although it probably is due to his large number of direct connections, many of which are to agents in Village 5 (closer to the producers, which means that on average agents there have more vessels to exchange than Village 8 residents).

With village size set to 500, the model creates many more agents, and there are more producers to make vessels. That means more vessels make it to Village 8, and some agents acquire large numbers of them, although most agents there have none or relatively few. As Figure 6 shows, the agents with large numbers of vessels are either directly connected to someone in a producing village, or connected through only one intermediary.

Agent 14084, a 60 year-old male, has the largest total number of vessels (109, 25 of which he still owned at the end of the simulation), and his spouse, Agent 14956 has the second largest (she only owned four at the end of the simulation, but had previously acquired and traded away 100). Agent 14956 is 52 years old, and is directly connected to Agent 17296, a female who lives in Village 2 (Figure 8). Both Agent 14084 and 14956 have high betweenness and degree centrality, which probably accounts, in part, for their success in acquiring vessels.

Agent 22425 has the highest betweenness of any Village 8 resident, and relatively high degree centrality as well. He is a 39 year-old male who was born in Village 2 and is directly connected to four different Village 2 residents, including his mother and sister. The combination of short path length to producers and his centrality in the network enabled success in acquiring vessels; he owned 12 vessels at the end of the simulation and had given away 58 more.

Agent 14837 stands out for having had relatively good success at acquiring vessels despite not having any close connections to producing villages (Figure 6). She is 53 years old and has acquired 45 vessels, although she only still owned one at the end of the simulation. Not only does she have a relatively long path length to the producers, she is not particularly central to the network; she has degree centrality of five, but her betweenness is only .002 (which puts her low on the graph in Figure 6 where there are so many points it is impossible to add a label). Although she is five nodes away from any agents in the producing villages, her path length to Village 3 is only two (through her husband, Agent 20318, to Agent 22707; Figure 8), which may account for her success in the exchange system.

Agent 19466 is a 46 year-old male who has high degree centrality (14) and betweenness (.03), but only moderate success at acquiring vessels compared to other agents with a path length of 2 (Figure 6). As Figure 9 shows, almost all of his direct connections are with other agents in Village 8, and the high betweenness appears to be the result of being on the shortest path between groups of Village 8 residents, which is unlikely to be an advantage in the exchange network. He does have a short path to a group of Village 1 residents through Agent 24327, who is married to his sister, and this apparently allowed him to have some success in exchange.

Four other agents are labeled in the bottom right graph of Figure 6 (Agents 20734, 23482, 26124, and 31349). These are all agents with very high degree centrality (Figure 9), and low or moderate betweenness. Despite their centrality, none of them were particularly successful in obtaining vessels. Three of them (20734, 26124, and 31349) have path lengths of three to producer villages, and 20 or fewer total vessels acquired. Agent 23482 has slightly higher betweenness, but a path length of 4, and was only able to acquire 12 vessels. All four of those agents have many close connections to other Village 8 residents (Figure 9), and relatively fewer connections to agents in distant villages compared to the networks of the agents shown in Figure 8 who were more successful in acquiring vessels.

Taken together, the examination of these individual agents and their networks suggests that both path length to producer villages and centrality are important in determining who is able to acquire vessels in the virtual exchange system. A short path to producers is important, but many individuals with direct connections to producing villages do not obtain many vessels. As figure 10 shows, there is a correlation between network centrality and total pots acquired, but the correlation is stronger for path lengths of one or two ($r2$ = .56 for betweenness, .31 for degree centrality) than for longer path lengths ($r2$ = .28 for betweenness, .11 for degree centrality).

Conclusion

The agent-based model that produced the networks analyzed here provides a rich source of data about the relationships between network structure and success in exchange. But the relationships are complex, and getting a clear picture of what is going on in the network produced by one run of the simulation is difficult. Generalizing is even more difficult. But a few points are clear. First, population size and the size of settlements has little effect on the degree distributions of the networks produced. The simulation always creates networks with highly skewed degree distributions where most agents have few direct links, but a few agents have many more. Betweenness is also not strongly affected by differences in population size, although the range of normalized betweenness values seems to increase slightly when population is small.

Increasing population size has a stronger affect on the number of agents with short path lengths from Village 8 to the producing villages. When population is small, a higher proportion of agents have connections that span the length of the virtual exchange system. This is because when settlement size is small, more agents are unable to find spouses in their home village, despite the built-in preference for village endogamy. This leads to increased movement between villages, which is the mechanism that accounts for long-distance connections in the model.

Path length to producers and centrality are both important in leading to success in acquiring vessels through exchange, but the relationships are complex. The individuals who obtain the most vessels usually have short path lengths to producing villages and above average centrality.

References

Allison, J R 2008 Exchanging Identities: Early Pueblo I Red Ware Exchange and Identity North of the San Juan River. In Varien, M D and Potter, J M (eds.) *The Social Construction of Communities: Agency, Structure, and Identity in the Prehispanic Southwest.* Lanham, Maryland: Alta Mira Press. pp. 41-68.

Allison, J R 2019 Ceramic Production and Exchange among the Virgin Anasazi, 30 Years Later, *Kiva*, 85(4):289-312. DOI: https://doi.org/10.1080/00231940.2019.1689660

Allison, J R 2020 Agent-Based Modelling of the Relationships among Kinship, Residence, and Exchange. In Glover, J, Rissolo, D, and Moss, J (eds.) Digital Archaeologies, Material Worlds (Past and Present): *Proceedings of the 2017 Computer Applications and Quantitative Methods in Archaeology Conference.* Tübingen: Tübingen University Press. pp. 229-240. DOI: http://dx.doi.org/10.15496/publikation-43203

Brughmans, T and Poblome, J 2016 Roman bazaar or market economy? Explaining tableware distributions through computational modelling, *Antiquity*, 90(350): 393–408. DOI: https://doi.org/10.15184/aqy.2016.35

Brughmans, T and Poblome, J 2016 MERCURY: an Agent-Based Model of Tableware Trade in the Roman East, *Journal of Artificial Societies and Social Simulation*, 19(1): 3. DOI: 10.18564/jasss.2953

Ibáñez, J J, Ortega, D, Campos, D, Khalidi, L and Méndez, V 2015 Testing complex networks of interaction at the onset of the Near Eastern Neolithic using modelling of obsidian exchange, *Journal of The Royal Society Interface*, 12(107): 20150210. DOI: https://doi.org/10.1098/rsif.2015.0210

Ortega, D, Ibañez, J J, Khalidi, L, Méndez, V, Campos, D and Teira, L 2014 Towards a Multi-Agent-Based Modelling of Obsidian Exchange in the Neolithic Near East, *Journal of Archaeological Method and Theory*, 21(2): 461–485. DOI: https://doi.org/10.1007/s10816-013-9196-1

Ossa, A 2013 Using network expectations to identify multiple exchange systems: A case study from Postclassic Sauce and its hinterland in Veracruz, Mexico, *Journal of Anthropological Archaeology*, 32(4): 415–432. DOI: https://doi.org/10.1016/j.jaa.2013.07.002

Watts, J and Ossa, A 2016 Exchange Network Topologies and Agent-Based Modeling: Economies of the Sedentary-Period Hohokam, *American Antiquity*, 81(4): 623–644. DOI: https://doi.org/10.1017/S0002731600101003

Wright. H and Zeder M 1977 The simulation of a linear exchange system under equilibrium conditions. In: Earle, T K and Ericson, J E (eds.) *Exchange systems in prehistory*. New York: Academic Press. pp. 233-253.

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Modeling Timescapes: Delineating Site Exploitation Territories (SET) by Using Topography Derivates and the Open-Source Statistical Language R

Jan Miera*
Historisches Seminar, Westf. Wilh.-Universität Münster
jmiera@uni-muenster.de

*previously published under the name
Jan Johannes Ahlrichs

Karsten Schmidt
eScience-Center, Universität Tübingen
karsten.schmidt@uni-tuebingen.de

Philipp Gries
SFB 1070 RessourcenKulturen, Universität Tübingen
philipp-matthias.gries@uni-tuebingen.de

Abstract

This paper provides a review of the history and archaeological applications of Site Exploitation Territories (SET) and presents the first seamless workflow for defining SET using the open source statistical language R. The concept of the SET was developed in the 1970s as an analytical tool to study finds from archaeological sites in relation to their geographical environment. A SET designates a time-distance based territory, which is visited on a daily basis by sedentary farmers or mobile groups as they deal with their subsistence. Therefore, the shape of a SET depends on the topography surrounding a site: In landscapes with a flat relief SET have an almost circular shape, in mountainous regions they are more distorted. Until recently, the determination of SET was performed manually using simple walking distances. Today, these results are hardly reproducible. The presented workflow is easy to use and calculates SET in a fast and reproducible way while taking into account walking speed and topography (slope) via Tobler's Hiking Function. It is tested on four digital elevation models (DEM) using 87 settlements dating to the pre-Roman Iron Age, located in the Baar region in south-western Germany. Based on the results of the case study, we recommend the use of open source CGIAR-CSI SRTM data. The results are nearly identical to those based on LiDAR data and require significantly less computational time for processing.

Keywords: Site Exploitation Territory, Settlement Archaeology, Archaeological Theory, Slope, Toblers Hiking Function

Introduction

With the advent of the Processual Archaeology in the 1960s, the research interest in economic issues started to grow increasingly (Trigger 2008: 386–444). Within the so-called "New Archaeology" scholars criticized the fact that archaeological studies on economy mostly focused on the analysis of material remains from single archaeological sites and did not discuss the finds in relation to their geographical environment (Higgs & Vita-Finzi 1972: 27–28; Jarman, Vita-Finzi & Higgs 1972: 61–62). At the University of Cambridge, a research group led by Eric S. Higgs developed a methodological concept, which enabled archaeologists to overcome this way of "isolated" analysis and to study archaeological sites in the context of their geographical environment. Inspired by the work of geographers (von Thünen 1826; Christaller 1933; Chrisholm 1968), archaeologists (Thomson 1939) and anthropologists (Lee 1969), they developed the concept of Site Exploitation Territories (SET) along with the Site Catchment Analysis (SCA) (Higgs & Vita-Finzi 1966: 23–29; Higgs et al. 1967: 12–19; Vita-Finzi & Higgs 1970; Roper 1979). The concept was developed and introduced in the series Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture (Higgs 1972; Higgs 1975; Jarman, Bailey & Jarman 1982). The term 'Site Exploitation Territory' refers to a territory that is defined by time-distances and is commonly used by the inhabitants of a site (Vita-Finzi & Higgs 1970: 7; Higgs & Vita-Finzi 1972: 30; Jarman 1972: 708). The fundamental difference between SCA and SET is that SCA does not consider time-distances. In SCA, the territory belonging to a site is not determined by walking distances but by a fixed radius of several hundred meters. Therefore, SCA works with circular territories and does not take into account the heterogeneity of the terrain that surrounds a site (Roper 1979; Brooks 1986; Miera 2020: 329–333).

Archaeological Applications

Researchers took the view that comparative studies on the changing human-environment relationships in mobile and sedentary societies require an analysis of the land use potential of territories belonging to archaeological sites (Vita-Finzi & Higgs 1970: 1; Higgs & Vita-Finzi 1972: 28–29; Foley 1977: 163). Within the framework of SET, they did not only study the availability and usage of natural resources in the catchment area of individual sites, but also how economic strategies of prehistoric societies contributed to environmental changes and how they interact (Vita-Finzi & Higgs 1970: 5; Higgs & Vita-Finzi 1972: 27). The concept of SET and SCA facilitated a description of the economic function of an excavated site through an in-depth analysis of archaeological finds with respect to the ecological and geographical environment of the site (Higgs & Vita-Finzi 1972: 28; Jarman 1972: 725; Jarman, Vita-Finzi & Higgs 1972: 61–62). Thus, sites were no longer considered as isolated case studies but as part of economic 'systems' (Jarman 1972: 715; Davidson 1981: 21–23). Based on a comparative analysis of archaeological sites dating to different epochs and periods Higgs and his co-researchers were able to obtain general conclusions about long-term trends in human-environment relationships (Jarman 1972: 714; Jarman 1976: 546). Geoff N. Bailey and Iain Davidson (1983: 88) summarized the strengths of SET:

1. Definition of a territory used on a daily basis within the framework of the subsistence strategies practiced at the site.

2. Analysis of the origin of natural resources recovered at archaeological sites.

3. Reconstruction of the vegetation history of the vicinity of a site in order to assess the changes in the botanical and zoological data from the site.

4. Reconstruction of the potentially available food for the inhabitants of a site and the subsistence strategies associated therewith.

5. Reconstruction of the function of a site (permanently inhabited, etc.).

6. Reconstruction of social and economic relations between sites within a regional settlement system.

In addition, the results of SET can be used in order to estimate potential site distributions (Jochim 1976; Tiffany & Abbott 1982). Altogether, the concept of SET provides an analytical approach, which enables researchers to link theory with data. Therefore, it qualifies as a ‚middle-range theory' (see Trigger 1995; Tschauner 1996).

Theoretical Premises

The concept of SET operates with the idea that human behaviour in the past can be described by 'laws' (Clarke 1968: 441–511; Higgs & Jarman 1975; Jarman 1976: 523). One of the main assumption is that people have a territorial behaviour and do not select sites at random (Vita-Finzi & Higgs 1970: 2; Higgs & Vita-Finzi 1972: 30; Jarman 1972: 706, 712). Furthermore, it is assumed that each site has an optimal geographic location considering its economic function. Consequently, it is expected that mobile groups, whose subsistence was pasture farming, preferred locations, which were favorable for grazing. On the other hand, archaeological sites from sedentary societies are expected to be located in areas suitable for agriculture

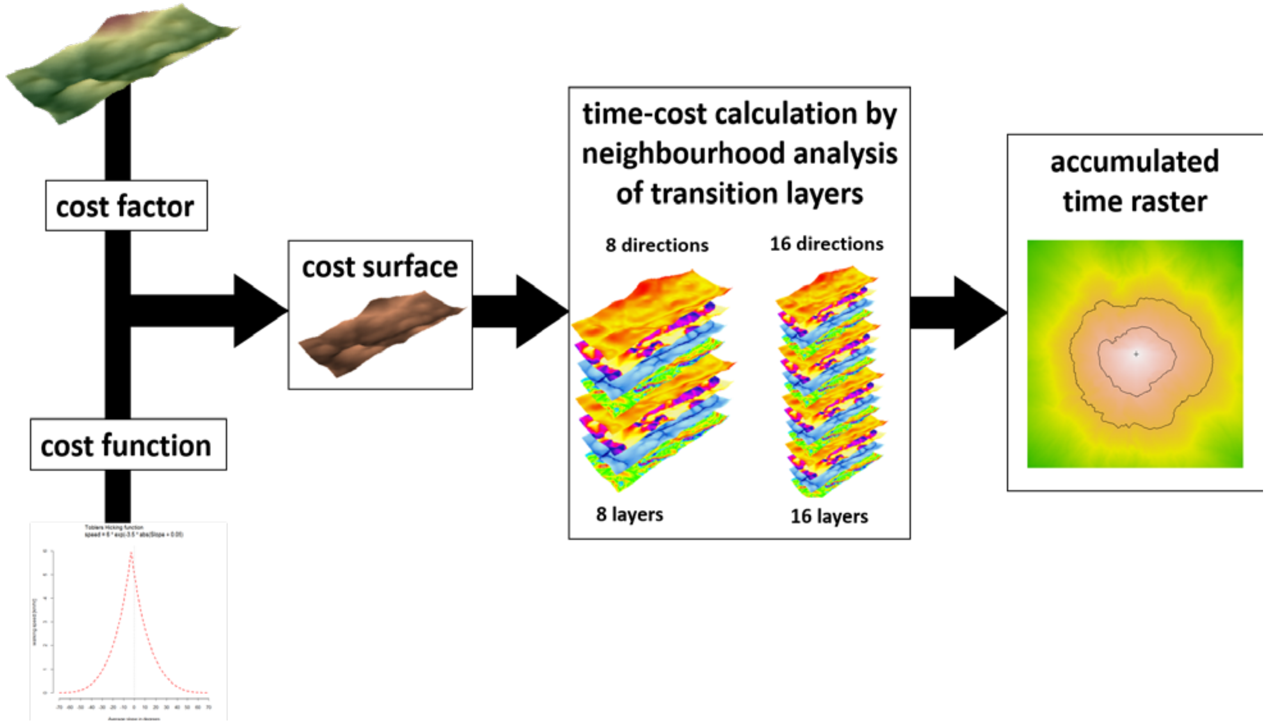

Figure 1. General workflow for time-cost analysis in four steps.

(Vita-Finzi & Higgs 1970: 2; Jarman 1972: 706; Jarman, Vita-Finzi & Higgs 1972: 62–63). Closely related to this premise is the notion that human action is determined by cost-benefit calculations and is constantly focused on efficiency, i. e. to meet ones economic needs with the lowest possible effort (Jarman 1972: 710 [citing Zipf 1965]; Jarman, Vita-Finzi & Higgs 1972: 62–63; Tiffany & Abbott 1982: 313–314). This behaviour ultimately leads to the premise that the probability to exploit an area decreases with distance (Vita-Finzi & Higgs 1970: 7; Jarman, Vita-Finzi & Higgs 1972: 62–63).

Time-Distance Factors

One of the key ideas of the concept is the assumption that the geographic scope of SET in mobile and sedentary societies differs from one another and can be described by time-distance factors. Referring to Lee (1969) on the !Kung San it was assumed that the SET of mobile groups includes a maximum radius of 10 km, which equates on flat terrain a maximum distance of two hours' walk (Higgs & Vita-Finzi 1972: 30–31; Jarman, Vita-Finzi & Higgs 1972: 62–63; Bailey & Davidson 1983: 91–92). With reference to Chrisholm (1968) Higgs and his team proposed a maximum radius of 5 km for sedentary societies (Higgs & Vita-Finzi 1972: 30–31; Jarman, Vita-Finzi & Higgs 1972: 62–63). In this context, they pointed out that the degree of exploitation within that radius decreases with increasing distance. Especially for sedentary societies, the nearest neighbourhood (radius < 1 km) is most important for the economic analysis (Higgs & Vita-Finzi 1972: 30–31; Jarman 1972: 713; Bailey & Davidson 1983: 92).

However, as Bailey and Davidson (1983: 93) pointed out, there are no universally valid time-distance factors for the analysis of prehistoric sites. The above mentioned time-distance factors represent idealized values whose ethnographic origin loses all its meaning as soon as they are applied to archaeological case studies (Davidson 1981; Bailey & Davidson 1983: 91). The differentiation between a 10 km SET for mobile groups and a 5 km SET for sedentary societies has to be understood as a model providing an analytical access to the discussion of the economic function of archaeological sites.

Field methods

Until the beginning of the 21th century the determination of SET was performed manually (see Valde-Nowak 2002: 65). In the 1970s, pedometers and maps were used (Jarman 1972: 712). Depending on the location of the site, four or more transects in different directions were used to determine its potential exploitation territory by analysing the walking distance within a specific time frame. Based on the experiences and notes from the field survey, 'time-contour lines' or 'isochronic distances' were drawn on a map (Jarman 1972: 713; Higgs 1975: appendix A; Bailey & Davidson 1983: 93). Obviously, this approach is very time consuming and expensive. In addition, the SET that were defined using this approach are subjective and no longer reproducible today. Bailey and Davidson summarized some of the major difficulties in determining the ‚isochronic distances': „In practice the walks were often carried out by students who were unfamiliar with the terrain, unused to walking long distances, and whose transects were influenced one way or another by modern roads and footpaths, barbed wire fences, bulls, unfriendly dogs or landowners, and the location of bars! The original Mt. Carmel study also had to allow for minefields and military manoeuvres" (Bailey & Davidson 1983: 93). In order to deal with some of these hurdles, Bailey and Davidson combined field surveys with the analysis of topographic maps. They applied rules developed by William W. Naismith, which were used by mountaineers to calculate time-distances. In principle, Naismith assumed that in two hours on flat ground a distance of 10 km can be covered on foot, for each 300 meters altitude difference an additional half hour is added: *„On a map at scale 1:25.000 with contours at 50 m intervals, isochronic limits may be calculated with a pair of compasses. With the compasses set at 1 cm, each unit of distance on the map is equivalent to 3 min. on the ground, and each contour is equivalent to an extra 5 min*" (Bailey & Davidson 1983: 94).

The form of a SET depends on the terrain surrounding a site. In landscapes with a balanced and flat terrain SET often have an almost circular shape. As one might expect, in mountainous regions this is not the case. Due to strong terrain differences SET tend to have a distorted form (Higgs & Vita-Finzi 1972: 33; Jarman 1972: 710, 713; Bailey & Davidson 1983: 93, 96). Because of that, SET based on time-distance factors provide a more realistic picture of the potentially used surroundings of a site in mountainous regions.

The concept and the development of SET and SCA had a huge impact in archaeological research (Findlow & Ericson 1980; Bailey 1983; Gilman & Thornes 1985; Brooks 1986; Bailey and Parkington 1988; Mytum 1988). However, in the 1990s and early 2000s, hardly any research was done with SET (Valde-Nowak 2002; Uthmeier, Ickler & Kurbjuhn 2008; Roubis et al. 2011; Cappenberg 2014; Henry, Belmaker & Bergin 2017; Miera et al. 2022). For example, in Germany, sites were not investigated with SET but with SCA (Gringmuth-Dallmer & Altermann 1985; Paetzold 1992; Fries 2005; Miera et al. 2020). Even though, this method does not do justice to the local topography, it was preferred in research, because back then there were no technical possibilities to model SET (Saile 1998: 101–103; Mischka 2007: 141–142). In contrast, SCA can be effortlessly performed in a Geographical Information System (GIS) since the early 1990s (Hunt 1992).

Computational Methods

The increasing availability of spatial data and fast developments in computing technologies as well as GIS enables implementing time-cost-functions in various ways. Well known commercial GIS software products offer different functions to compute cost surfaces and cost distances to estimate the effort needed to cross a certain landscape (Rogers, Collet & Lugon 2014; Rogers, Fisher & Huss 2014). Especially with the increased availability of high resolution as well as large-scale DEMs as provided by the Shuttle Radar Topographic Mission (Rodriguez et al. 2005; Farr et al. 2007; Jarvis et al. 2008) the methods and their results become more and more interesting for the scientific community to study societies, functions and resources. In general, the common workflow for time-cost analysis comprises four steps (Figure 1). The first step is to create a cost surface based on an input dataset and an arbitrary cost function measuring cost in time. The second step is a neighbourhood analysis based on a set of multiple transition layers. The number of these layers depends on the number of moving directions from the centre cell

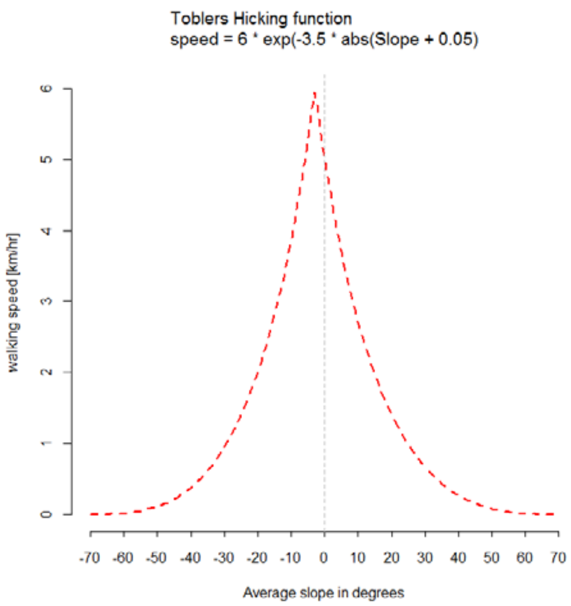

Figure 2. Tobler's Hiking Function (Tobler 1993).

to the neighbouring ones. The chosen cell is the surrounding one being reachable by the smallest expenditure of time. Thirdly, accumulating the time along the fastest path provides the final time-cost raster. Finally, the visualization of the spatial expansion of the moving patterns results from isochrones.

However, for many purposes using commercial software is cost and time intensive. In addition, using different software implementations of time-cost analysis on the same data produces dissimilar results that are incommensurable (Herzog 2013). Therefore, we implemented one of the most famous time-distance functions in an open source environment (Programming Language R) to address a wide-range of scientists and to enable a potential use in analytical questions.

Tobler Hiking Function

As mentioned before, there are various ways to apply and/or implement least-cost analysis within a wide-range of archaeological research. There are numerous studies using the hiking function by Waldo R. Tobler (1961; Herzog 2013; Herzog 2014) first implemented by Gorenflo and Gale (1990). Tobler (1993) developed an empirical model based on the marching data of the Swiss military given by Imhof (1950). Marching time depends on multiple factors, such as length and quality of path, altitude difference, weather conditions and darkness as well as marching competence and luggage. In addition, hiking speed is greater for short distances than for long-lasting marches and small groups cover distances faster than columns (Imhof 1950). The Tobler Hiking Function is the empirical quantification of the walking velocity to cross a certain terrain by using a DEM as well as the first derivative (dh/dx):

$$V = 6e\{-3.5 \text{ abs } (s + 0.05)\}$$

where V is the walking velocity in km/h, e is the base of the natural logarithms, and s is dh/dx [dh and dx must be measured in the same unit; slope] (Tobler 1993). This formula calculates a maximum velocity of around 6 km/h on gently downslope direction from -5 to -2 degrees and on flat terrain around 5 km/h (Fig. 2). In addition, Fig. 2 also shows a decreasing speed of hiking with an increasing slope gradient because overcoming steeper slopes is time-consuming and exhausting. The empirical data of Imhof (1950) is limited to small groups hiking on defined paths and ways with average speed of 4.5 to 5 km/h on flat terrain. To address off-path traveling, reducing mean hiking speed to 3 km/h (Imhof 1950), Tobler (1993) argued to include an off-path multiplier of 0.6.

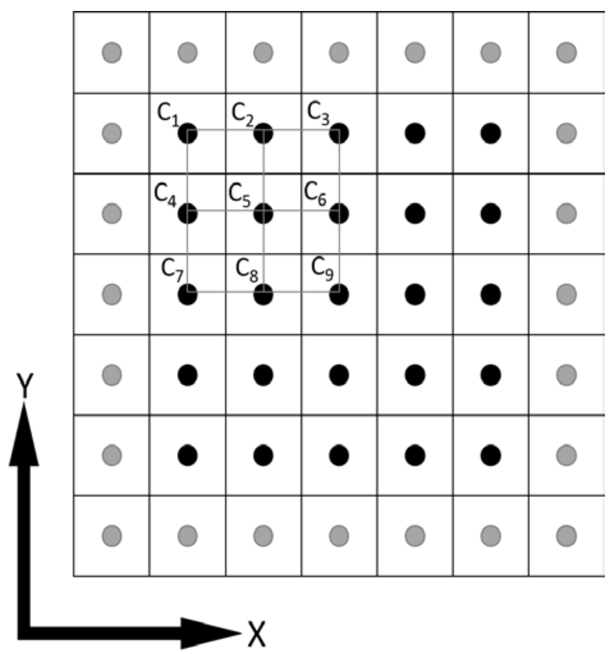

Figure 3. Moving Window approach for deviating terrain attributes (e.g. slope) from a digital elevation model (see Behrens 2003).

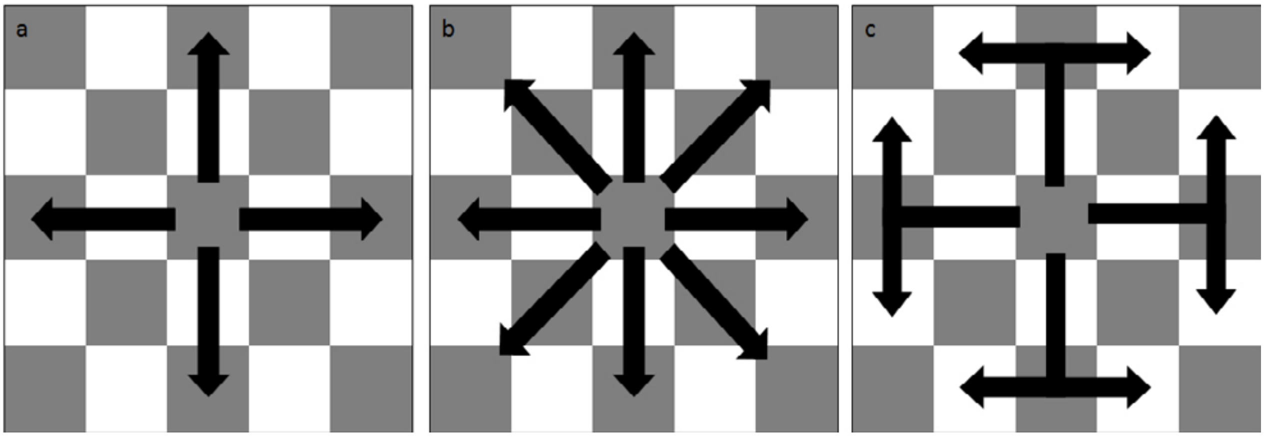

Figure 4. Moving characteristics using four (a, rook move), eight (b, queen move) and 16 directions (c, knight move).

Main Cost Factor: Slope

According to Tobler (1993), slope is the foundation of time-cost analysis. Therefore, almost all archaeological studies use slope as a cost factor (Herzog 2014). Slope is an anisotropic cost factor depending on the directions of movement (Herzog 2013). However, there is a huge number of different slope algorithms using pixel-based analysis, each addressing particular questions and certain landscape conditions or data quality. Slope is the first derivative of the terrain representing the vertical change of the elevation (Behrens 2003).

The ultimate principle of deriving slope from an elevation model is calculating the difference of height between the centre cell and its surroundings. Depending on the slope algorithm chosen, the number and combination of the cells nearby varies. The most common slope algorithms are the mean slope gradient (Zevenbergen & Thorne 1987) for smooth terrains as well as the maximum slope gradient (e.g. Guth 1995) for identifying streamlines (Behrens 2003). Both approaches are using a moving window technique to calculate a slope angle (Fig. 3) between the centre cell and its neighbourhood. Using Zevenbergen and Thorne (1987), the slope angle bases on accounting the cardinal cells only (C2, C4, C6, C8, Fig. 3), whereas the maximum slope algorithm by Guth (1995) uses diagonal neighbours additionally. Using cardinal neighbours has the advantage of including the nearest pixels only, resulting in a high local accuracy, but tends to get noisy if the terrain is very heterogeneous or the quality of the DEM is low. This slope angle is the average slope gradient of the neighbourhood. In contrast, the maximum slope angle results from the pixel showing the maximal difference in altitude to the centre of the moving window (Behrens 2003). Besides these two widespread approaches, there are other popular algorithms as Fleming and Hoffer (1979) as well as Ritter (1987) for smooth surfaces and Horn (1981) for rough surfaces, both being included in the r-package "raster" (Hijmans 2016).

Other Cost Factors

Besides slope as an anisotropic cost factor, there are isotropic cost factors including topographic, social and cultural factors, which influence crossing the landscape (Herzog 2013). Particular types of land cover or water bodies complicate traversing any region. The water volume of mountain streams can vary between passable and impassable during the day. Besides, vegetation age, stand diversity and density influence the hiking speed and energy effort. Moreover, substrate, bedrock, subsoil and general underground cause tough sledding (Imhof 1950). In addition, the terrain includes areas hardly passable for human beings. Pixels of steep slopes represent areas with lower velocity. Allocating these zones as impassable barriers leads to their exclusion from the time-cost analysis. In addition to anisotropic factors, the time-cost analysis uses friction layers to include isotropic cost factors that influence spatial moving patterns.

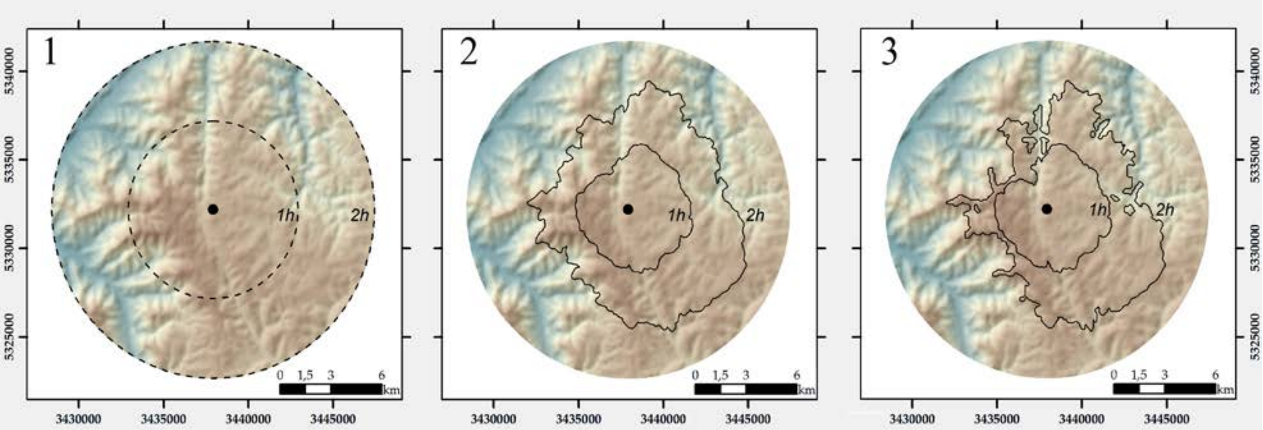

Figure 5. Three plots of time-cost-analysis using different terrain information. Excluding the terrain results in circular isochrones around the initial point (1). By including the slope gradient, the covered distances per time interval continue along the terrain (2). The exaggeration of steep slopes creates moving patterns continuing strictly along high-angle hillsides (3). The contour lines represent the covered distance per hour.

Time-cost calculation

As mentioned above, slope and the Tobler Hiking Function are a reliable foundation of numerous time-cost analysis (Herzog 2013; Herzog 2014). Therefore, we use the Tobler Hiking Function to calculate the velocity to cross each pixel cell using a slope raster dataset. The Tobler Hiking Function is best suited for flat terrain over gently to moderate slopes (Herzog 2014). Thus, for reducing errors at steep slopes (e.g. >16°) we implemented an optional damping cost factor lowering the hiking velocity tremendously at these areas. The (damped) velocity raster is the final cost surface.

The final step computing the time-cost surface by a stepwise or cell-by-cell-based approach to account for traversing the landscape is the most time and computational intensive part. As the number of moving directions from one cell to a neighbouring cell is relevant, four, eight and 16 directions are differentiated. The naming of moving characteristics originates from chess moves. Rook move (four directions) means just following cardinal directions, queen move (eight directions) additionally enables diagonally shifting and knight move (16 directions) respects a combination of cardinal and diagonal movements (Fig. 4). An increasing number of directions results in a growing computational time but also in moving patterns of humans being more realistic.

To address the spatial resolution of each individual DEM dataset we implemented a geo-correction of the time-cost raster considering the cardinal and diagonal movement through pixel cells. Finally, each pixel of the time-cost raster contains the accumulated time needed to reach it from the initial location.

Fig. 5 exemplifies the SETs of a one-hour and a two-hour hike starting from a neolithic test site in the Black Forest disregarding (1) and respecting (2, 3) the local terrain. Hence, the scaling down of the potential exploitation territory is 23.3% considering the local terrain. Including a damping factor of 16° (3) effects another reduction of 4% from original 254 km² to 186.5 km². The spatial restriction enables the purposive focus on particular questions.

Methodical workflow and script example

The following R-script is a stepwise implementation of the Tobler Hiking Function into spatial time-cost analysis using a user-specific DEM and/or a slope gradient dataset (cf. Supplementary Material).

A successful application of the script requires the installation of all packages of Tab. 1 on a local machine or given computational environment and their implementation via library command. Note: Missing lines below are script related comments.

```
- R-Script Part 1 - Libraries
[6]       library(raster)
[7]       library(gdistance)
[8]       library(sp)
[9]       library(lattice)
```

Package	Version	Description	Citation
raster	2.5–8	Geographic Data Analysis and Modeling	Hijmans 2016
gdistance	1.1–9	Distances and Routes on Geographical Grids	Van Etten 2015
sp	1.2–3	Classes and Methods for Spatial Data	Pebesma & Bivand 2005 Bivand et al. 2013
lattice	0.20–34	Trellis Graphics for R Spatial and Spatio-Temporal	Sarkar 2008
gstat	1.1–3	Geostatistical Modelling, Prediction and Simulation	Pebesma 2004
rgeos	0.3–20	Interface to Geometry Engine – Open Source (GEOS)	Bivand & Rundel 2016

Table I: R-packages used for the delineation of Site Exploitation Territories (SET).

Spatial Dataset	Minimum	Maximum	Mean	Standard Deviation
DEM [m]	766	1177	995.76	73.03
Slope [°]	0.11	33.14	8.08	4.87

Table II: Zonal statistics of the terrain as example of the descriptive analysis of the spatial datasets (Digital Elevation Model and Slope) using the Minimum, Maximum, Mean and Standard deviation measurements of the spatial area defined by the first walking hour.

```
[10]      library(gstat)
[11]      library(rgeos)
```

The implementation and visualisation of Tobler's Hiking Function results from the following lines.

```
 – R-Script Part 2 – Tobler's Hiking
Function
 [29]      ToblersHikingFunc-
tion <- function(x){ 6 * exp(-3.5 *
abs(tan(x*pi/180) + 0.05)) }
 [32]      TheoreticalSlopes <- seq(-
70,70,1)
 [33]      WlkSpeed <- ToblersHiking-
Function(TheoreticalSlopes)
 [34]      plot(TheoreticalSlopes,
WlkSpeed, type="l", col ="red", lwd = 2,
lty="dashed",
     ylab="walking speed [km/hr]",
xlab="Average slope in degrees", axes=F)
 [35]      axis(1, tck=-.01, at= Theore-
ticalSlopes[seq(1,length(TheoreticalSlo-
pes),10)],
     labels= TheoreticalSlopes[-
seq(1,length(TheoreticalSlopes),10)])
 [36]      axis(2)
 [37]      abline(v=0, lty="dashed", col
="gray")
 [38]      title(expression(„Toblers
Hiking function\nspeed = 6 * exp(-3.5 *
abs(Slope + 0.05)"))
```

The user has to adjust the general setting related to working directories (1), datasets (2–3) and environmental variables (4). A slope gradient dataset is optional. If no slope data is given, the user has to choose a slope algorithm by defining the number of neighbours (4 or 8 neighbours) in line [66]. The input of the X- and Y-coordinates defines the initial spatial location (e.g. settlement, artefact location, etc.) for the time-cost-analysis and means the starting point for site exploitation.

```
 – R-Script Part 3 – Settings (1) direc-
tories
 [45]      InDir <- "Path/To/Your/Input-
Data"
 [46]      OutDir <- "Path/To/Your/Out-
putData"


 – R-Script Part 3 – Settings (2) input
data
 [50]      DEM           <- "FileNameOf-
DigitalElevationModel.rasterformat"
```

```
[51]      SLOPE   <- “FileNameOfSlopeG-
radient.rasterformat”
[52]      POINT   <- c(X,Y-CoordinateO-
fInitialPoint)
```

```
– R-Script Part 3 – Settings (3) output
data
[55]      TCR     = “FileNameOfTimeCos-
tRaster”
[56]      SLG     = “FileNameOfSlopeRa-
ster” # optional
[57]      CTL     = “FileNameOfContour-
Lines”
[58]      rdt     = “RasterDatatype”
```

```
– R-Script Part 3 – Settings (4) envi-
ronmental variables
[66]      NumbersOfNeigbors     <- 8
[69]      Damping
<- TRUE
[70]      DampingFactor         <- 16
[78]      NumberOfDirections    <- 8
[82]      TimeOfInterest
<- 2
[88]      NumberOfIsochrones    <- 2
[89]      IntervallOfIsochrones
<- 1
```

For handling big datasets, we implemented an isochronic mask layer to reduce the dataset to the related area of interest to reduce the computational demand and effort.

```
– R-Script Part 4 – read DEM
[95]      setwd(inDir)
[98]      rDEM <- raster(DEM)
```

```
– R-Script Part 4 – read/create SLOPE
[101]     rSLOPE <- NULL
[102]     if (nchar(SLOPE) > 0) {
[103]             rSLOPE <- raster(SLO-
PE)
[104]     } else {
[106]             if(!is.na(projecti-
on(rDEM))) {
[107]                     rSLOPE <- ter-
rain(rDEM, opt=’slope’, unit=’degrees’,
neighbors=NumberOfNeighbors)
[108]             } else {
[110]     print(“PROJECTION ERROR: no
projection is set for ELEVATION input
file.”)
[111]             }
[112]     }
```

```
– R-Script Part 4 – set initial spatial
location
[115]     SPATIALPOINT <- data.fra-
me(x=POINT[1],y=POINT[2])
[116]     coordinates(SPATIALPOINT) <-
~ x+y
[117]     projection(SPATIALPOINT) <-
projection(rDEM)
```

```
– R-Script Part 4 – Reduce dataset to
AOI (Area-Of-Interest)
[120]     rSLOPE4TimeCost <- rSLOPE
[121]     rDEM4Statistics <- rDEM
[123]     if (TimeOfInterest > 0) {
[126]             maxHikingDistan-
ce <- round(max(WlkSpeed)* (TimeOfInte-
rest+0.25)*1000)
[129]             bufferMaxHikingDistance
<- buffer(SPATIALPOINT, maxHikingDistance)
[132]             rDEM_clip <-
crop(rDEM,extent(bufferMaxHikingDistance))
[133]             rSLOPE_clip <-
crop(rSLOPE,extent(bufferMaxHikingDistan-
ce))
[136]             rDEM4Statistics <-
rDEM_clip
[139]             rSLOPE4TimeCost <-
rSLOPE_clip
[140]     }
```

The next part calculates the velocity of crossing the landscape based on the delineated slope raster while including a slope-based damping factor if chosen. Additionally, some time and space conversions are needed for the final estimations. Finally, spatial correction and time-cost accumulation is done while calculating the accumulated cost surface. Some visualisation outputs are provided via plot-function to self-test and validate the computed spatial datasets.

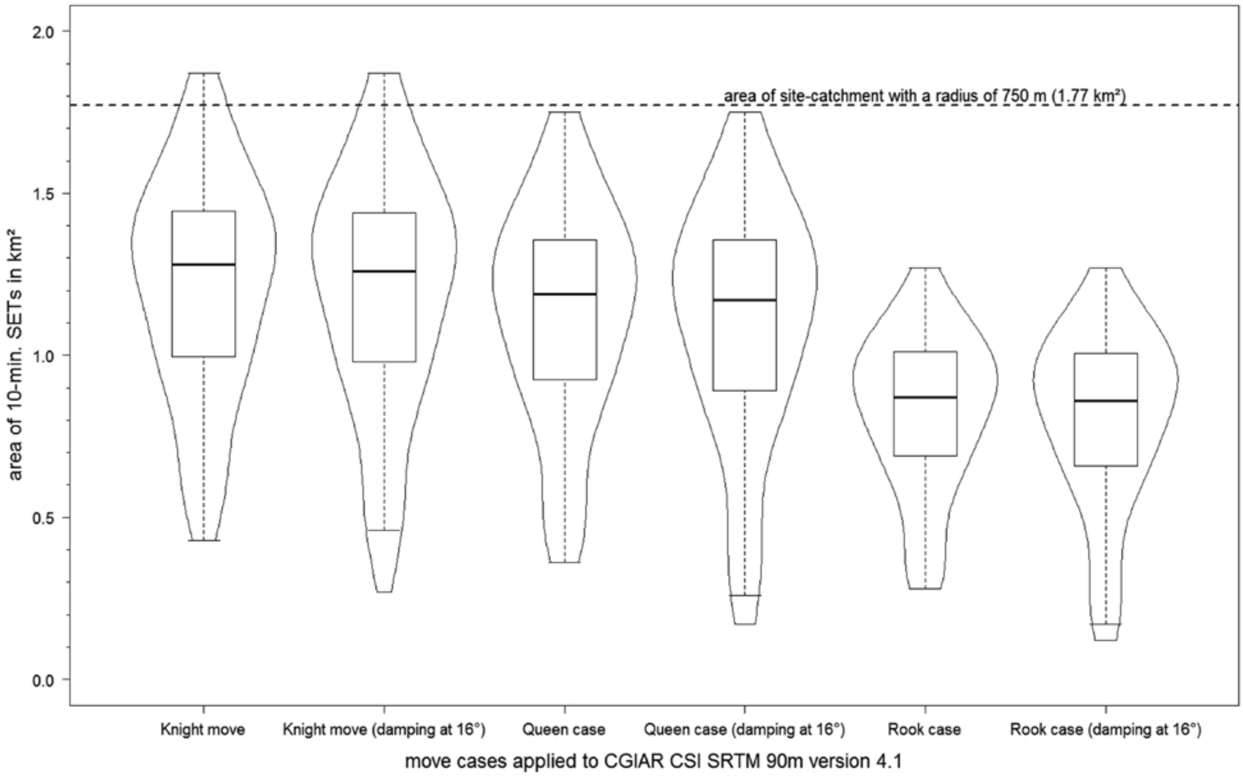

Figure 6. Applying different move cases and damping factors to CGIAR-CSI SRTM version 4.1 (90 x 90 m).

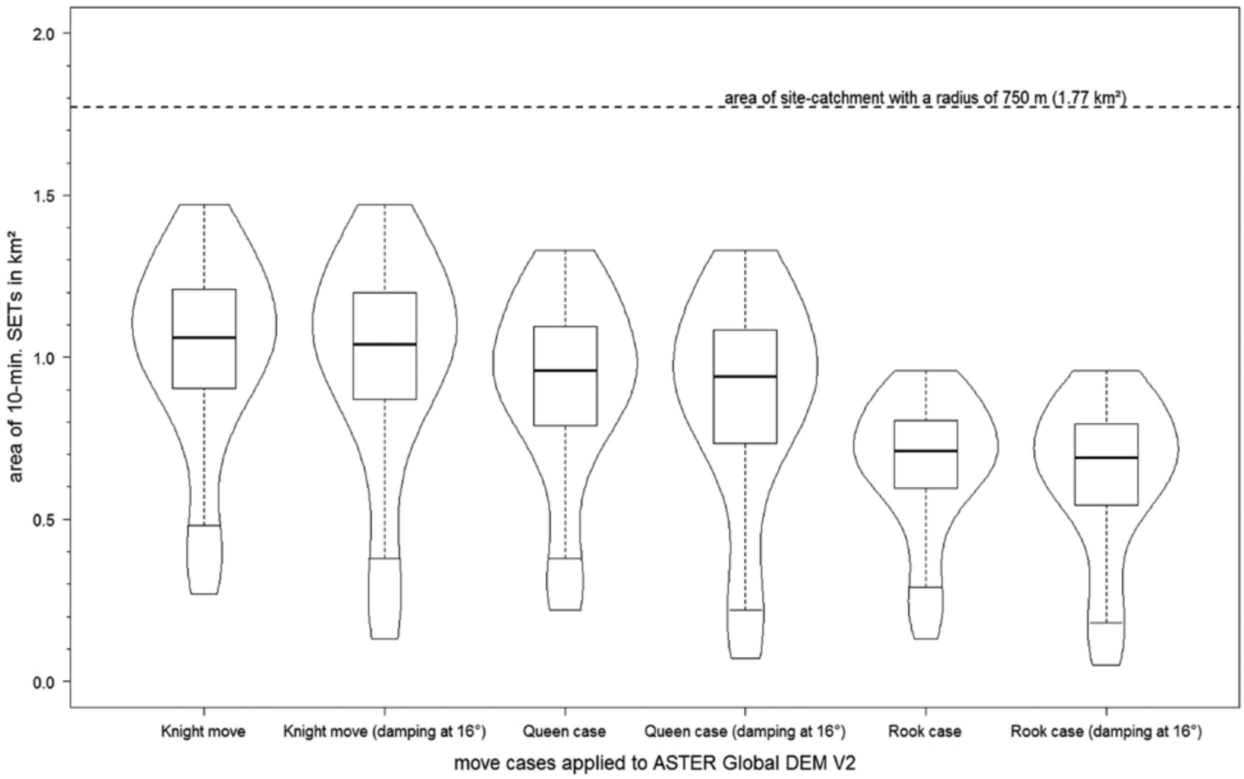

Figure 7. Applying different move cases and damping factors to ASTER Global DEM V2 (30 x 30 m).

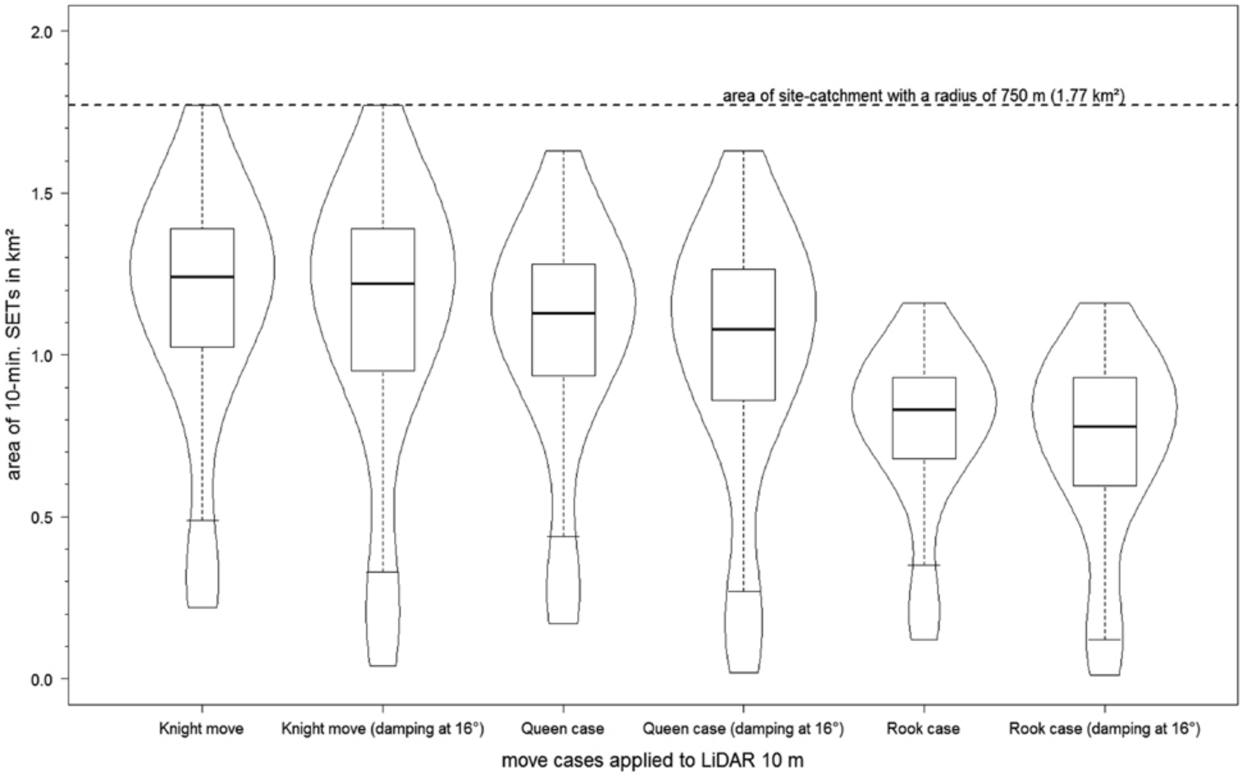

Figure 8. Applying different move cases and damping factors to LiDAR data (10 x 10 m).

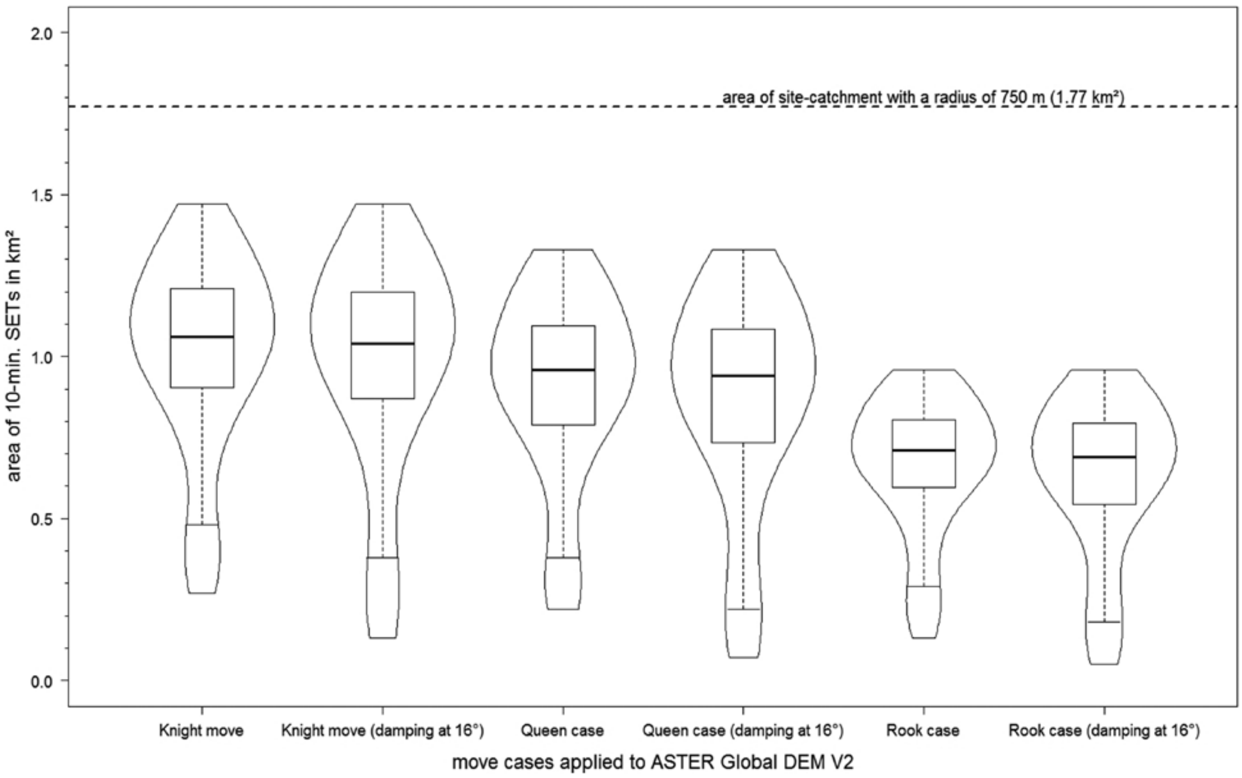

Figure 9. Applying different move cases and damping factors to DLR SRTM X-SAR DEM (25 x 25 m).

Digital elevation model	Move case	Damping factor	Minimum	1st quantile	Median	Mean	3rd quantile	Maximum	Stand. Deviation
SRTM 90 m	Knight move	none	0.430	0.995	1.280	1.215	1.445	1.870	0.339
	Knight move	16°	0.270	0.980	1.260	1.196	1.440	1.870	0.364
	Queen case	none	0.360	0.925	1.190	1.123	1.355	1.750	0.335
	Queen case	16°	0.170	0.890	1.170	1.099	1.355	1.750	0.368
	Rook case	none	0.280	0.690	0.870	0.823	1.010	1.270	0.244
	Rook case	16°	0.120	0.660	0.860	0.804	1.005	1.270	0.271
ASTER Global DEM V2	Knight move	none	0.270	0.905	1.060	1.011	1.210	1.470	0.304
	Knight move	16°	0.130	0.870	1.040	0.975	1.200	1.470	0.346
	Queen case	none	0.220	0.790	0.960	0.904	1.095	1.330	0.293
	Queen case	16°	0.070	0.735	0.940	0.863	1.085	1.330	0.335
	Rook case	none	0.130	0.595	0.710	0.661	0.850	0.960	0.212
	Rook case	16°	0.050	0.545	0.690	0.627	0.795	0.960	0.244
LiDAR 10 m	Knight move	none	0.220	1.03	1.240	1.148	1.390	1.770	0.386
	Knight move	16°	0.040	0.950	1.220	1.107	1.390	1.770	0.431
	Queen case	none	0.170	0.935	1.130	1.047	1.280	1.630	0.364
	Queen case	16°	0.020	0.860	1.080	0.996	1.265	1.630	0.408
	Rook case	none	0.120	0.680	0.830	0.767	0.930	1.160	0.262
	Rook case	16°	0.010	0.595	0.780	0.717	0.930	1.160	0.300
DLR SRTM X-SAR	Knight move	none	0.330	0.925	1.080	1.031	1.245	1.470	0.290
	Knight move	16°	0.210	0.880	1.040	0.997	1.230	1.470	0.325
	Queen case	none	0.250	0.795	0.940	0.891	1.100	1.340	0.282
	Queen case	16°	0.100	0.755	0.910	0.846	1.090	1.340	0.324
	Rook case	none	0.190	0.550	0.690	0.647	0.790	0.970	0.204
	Rook case	16°	0.050	0.480	0.650	0.604	0.785	0.970	0.243

Table III: Comparison of site exploitation territory sizes using different move cases, damping factors and different digital elevation models.

```
 – R-Script Part 5 – time cost analysis
  [147]     rVelocity.kmh <- calc(rSLOPE-
4TimeCost, ToblersHikingFunction)
  [150]     rVelocity.ms <- calc(rVeloci-
ty.kmh, fun=function(x) { ((x*1000)/3600)
})
  [156]     if (Damping) {
  [157]            rDamping <- rSLOPE4Ti-
meCost
  [158]            rDamping[rDamping >
DampingFactor]  = 1000
  [159]            rDamping [rDamping <=
DampingFactor]  = 1
  [160]            rVelocity.ms <- rVelo-
city.ms/rDamping
  [162]     }
  [166]     lTransition <- transit-
ion(rVelocity.ms, transitionFunction=mean,
                                   direc-
tions=NumberOfDirections)
  [170]     lGeoCorrection <- geoCorrec-
tion(lTransition, type=”r”)
  [171]     rAccumulatedCostSurface.s <-

 – R-Script Part 6 – zonal statistics
  [189]     zonalStatistics   <- data.
frame(matrix(0,2,5))
```

```
  [190]     statNames <- c(‚1st
hour‘,‘min‘,‘max‘,‘mean‘,‘sd‘)
  [191]     names(zonalStatistics) <-
statNames
  [192]     zonalStatistics[1,1] <- ‚DEM‘
  [193]     zonalStatistics[2,1] <- ‚SLO-
PE‘
  [196]     rasterZones <- rAccumulated-
CostSurface.h
  [197]     rasterZones[rAccumulatedCost-
Surface.h <= 1] = 1
  [198]     rasterZones[rAccumulatedCost-
Surface.h > 1]   = 2
  [201]     for(st in 2:length(statNa-
mes)) {
  [202]     zonalStatistics[1,st] <- zo-
nal(rDEM4Statistics, rasterZones, statNa-
mes[st])[1,2]
  [203]            zonalStatistics[2,st]
<- zonal(rSLOPE4TimeCost, rasterZones,
statNames[st])[1,2]
  [204]     }
  [206]     print(zonalStatistics)
```

The final commands produce an output of raster and vector files in the given output directory.

```
 – R-Script Part 7 – write files
  [212]     setwd(outDir)
  [213]     writeRaster(rAccumulatedCost-
Surface.h,TCR, format=rdt)
  [214]     if (nchar(SLOPE) == 0) {
  [215]            writeRaster(rSLOPE4Ti-
meCost,SLG, format=rdt)
  [216]     }
  [217]     shapefile(vContourLines,filena-
me=CTL)
  [217]     shapefile(vContourLines,filena-
me=CTL)
```

Case Study: Pre-Roman Iron Age Land Use in the Baar Region and Adjacent Landscapes

The practical application of the script can best be described using different scenarios based on an archaeological test dataset from south-western Germany. As an example, we will use 87 sites from the pre-Roman Iron Age from the Baar and the adjacent landscapes. The prehistoric and early historic land use of this area was studied during the first funding phase of the Collaborative Research Center 1070 with both archaeological and pedological methods (Ahlrichs et al. 2016; Henkner et al. 2017; Knopf & Ahlrichs 2017; Ahlrichs, Riehle & Sultanalieva 2018; Ahlrichs et al. 2018a; Ahlrichs et al. 2018b; Henkner et al. 2018a; Henkner et al. 2018b; Miera et al. 2019; Miera 2020). The region is particularly suitable for the application of the described SET workflow, because it covers the gentle rolling terrain of the Baar and extends into the adjacent low mountain ranges of the Black Forest and the Swabian Jura, where the topography is far more heterogeneous.

Each of the following scenarios focuses on the size of the SET. Based on four different DEMs, it will be shown how the move cases affect the time-cost-raster and therefore the shape of the SET (see also Becker et al. 2017). In addition, it can be demonstrated how the grid cell sizes influence the final results and how the resolution of the cells affects the time needed for processing the data.

For the analysis, we used both the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM Version 2 (GDEM V2) with a resolution of 30 x 30 m, as well as data from the Shuttle Radar Topographic Mission (CGIAR-CSI SRTM) with a cell size of 90 x 90 m provided by the National Aeronautics and Space Administration (NASA). In addition, we used the SRTM X-SAR DEM from the German Aerospace Center (DLR) with a cell size of 25 x 25 m and a DEM with a resolution of 10 m based on Light Detection And Ranging (LiDAR) technology, kindly provided by the State Office for Cultural Heritage Baden-Wuerttemberg.

Atmospheric noise, radar shadowing effects as well as vegetative and anthropogenic structures have been removed from the CGIAR-CSI SRTM and LiDAR data (Rodriguez et al. 2005; Farr et al. 2007; Jarvis et al. 2008; Hesse 2012). Regional studies from the US and Thailand have shown that even in low mountain ranges CGIAR-CSI SRTM data have a height accuracy of ± 7 m and thus very well reflect the general terrain trend (Gorokhovich & Voustianiouk 2006). Comparable minor errors can be demonstrated for the GDEM2 data (Gesch et al. 2012; Li et al. 2012; Purinton & Bookhagen 2017).

In contrast to the three DEM mentioned, the DLR X-SAR data appear much noisier. Technically, this dataset is a digital surface model, because the elevation data include urban structures, vegetation and other objects (Ludwig & Schneider 2006). In addition, steep west-facing slopes are affected by radar shadows. Here, errors of up to 200 m can be demonstrated (Ludwig and Schneider 2006: 343). In general, the DLR X-SAR data have a horizontal accuracy of ± 20 meters (Keydel, Hounam & Werner 2000; Rabus et al. 2003).

The results of our comparative analysis can be seen in Figures 6-9 as well as in Table 3. With respect to the different move cases the following general tendencies can be observed: The Knight move always produces the largest SET, followed by slightly smaller SET produced by the Queen case. Using the rook case will result in very small SET. This can be seen in DEM with a high resolution of 10 m as well as in those with a cell size of 90 m. In addition, it can be stated that the resolution of the elevation models leads only to slightly different results. On average, the SET based on the GDEM2 and the DLR X-SAR data cover an area of about 1 km². The SETs obtained using the CGIAR-CSI SRTM data and the LiDAR data are on average 0.23 to 0.27 km² larger. This observation is important, because the script is able to calculate SET for 87 sites in less than five minutes (Windows 7, 2.70 GHz, 8GB Ram, SSD) using the CGIAR-CSI SRTM data. In contrast, the processing of the LiDAR data took hours for the same number of sites.

Finally, as one might expect, the use of a damping factor results in a slight reduction of the modeled SET. This is recognizable in particular in the minimum values. The fact that the use of a damping factor generally has only a small influence on the sizes of the modeled SET can have different reasons. On the one hand, it should be remembered that the SET were modeled for small areas with a time-distance of ten minutes. In principle, it can be assumed that with larger time-distances greater deviations can be observed between the SET modeled with and without a damping factor. On the other hand, it is strongly affected by the general topographic arrangement around the given study sites especially in heterogeneous landscapes accompanied with steep slope areas the effect of the damping will be increased and only the valley ranges will be used by the algorithm. In general, damping effects can be enhanced by choosing a small slope and/or by increasing the weight of the damping factor. However, one has to decide on their own for each case study, which values they want to work with.

Conclusion and Remarks

Even though the concept of site exploitation territories is now almost 50 years old and remains central to archaeological research. On the basis of an intensive literature research, it could be shown that this concept was primarily used to discuss economic research questions. These were often linked to natural deterministic assumptions. In addition, analyzes are often based on the premise that people always make rational choices and choose the optimal path with the least effort to meet their everyday economic needs. However, the concept of the SET plays not only a central role in system theory within processual archaeology. In principle, it can also be combined with modern approaches from post-processual archaeology, which lie beyond economic questions. For example, the factors space and time can easily be combined with phenomenological research as well as viewshed analyzes and thus contribute to studies on landscape perceptions. In addition, the R script can also be used to model territories that were surveyed by archaeologists. Based on the case study of the pre-Roman Iron Age settlement of the Baar using different DEM products with resolution ranging from 10–90 m, the use of CGIAR-CSI SRTM data is recommended. The proposed workflow is able to process DEM with a resolution of 90 m for a large datasets within minutes. In addition, this dataset produces nearly identical results as the high-resolution LiDAR data. Altogether, we encourage our colleagues to use the R-script presented in this paper. Please feel free to adapt it to your own needs and to expand and improve its functionality by adding new lines of code.

References

Ahlrichs, J J, Henkner, J, Teuber, S, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2016 Archaeological and Archaeopedological Approaches to Analyze the Development of Marginal Areas in Prehistory: A Case Study from the Western Baar, SW Germany. In: Kolodziejczyk, P and Kwiatkowska-Kopka, B (eds) *Landscape in the past & forgotten landscapes. Cracow Landscape Monographs 2: Landscape as impulsion for culture: research, perception and protection*. Cracow: Institute of Archeology Jagiellonian University, pp. 39–49.

Ahlrichs, J J, Riehle, K and Sultanalieva, N 2018 The Production of Liminal Places: An Interdisciplinary Account. *Ethnographisch-Archäologische Zeitschrift*, 56(1–2): 205–242.

Ahlrichs, J J, Henkner, J, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2018a L'utilisation des terres pendant la période néolithique sur la colline du Fürstenberg à la bordure sud du Baar en Allemagne du sud-ouest. In: Lemercier, O, Sénépart, I, Besse, M, Mordant, C (eds) *Habitations et habitat du Néolithique à l'âge du Bronze en France et ses marges. Actes des IIe Rencontres Nord/Sud de Préhistoire récente, Dijon, 19.–21. Novembre 2015*. Toulouse: Archives d'Écologie Préhistorique, pp. 619–622.

Ahlrichs, J J, Henkner, J, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2018b Bronzezeitliche Siedlungsdynamiken zwischen der Baar und angrenzenden Naturräumen. In: Neumann, D, Nessel, B and Bartelheim, M (eds.) *Bronzezeitlicher Transport. Akteure, Mittel und Wege. RessourcenKulturen 8*. Tübingen: Tübingen University Press, pp. 269–303. DOI: 10.15496/publikation-26722

Bailey, G N 1983 *Hunter-Gatherer Economy in Prehistory: A European Perspective*. Cambridge: Cambridge University Press.

Bailey, G N and Davidson, I 1983 Site Exploitation Territory and Topography: Two Case Studies from Palaeolithic Spain. *Journal of Archaeological Science*, 10(1): 87–115. DOI: 10.1016/0305-4403(83)90044-4

Bailey, G N and Parkington, J 1988 *The Archaeology of prehistoric coastlines*. Cambridge: Cambridge University Press.

Becker, D, De Andrés-Herrero, M, Willmes, C, Weniger, GC and Bareth, G 2017 Investigating the Influence of Different DEMs on GIS-Based Cost Distance Modeling for Site Catchment Analysis of Prehistoric Sites in Andalusia. *International Journal of Geo-Information*, 6(2): 36. DOI: 10.3390/ijgi6020036

Behrens, T 2003 *Digitale Reliefanalyse als Basis von Boden-Landschafts-Modellen am Beispiel der Modellierung periglaziärer Lagen im Ostharz. Boden und Landschaft 42*. Giessen: Universität Giessen.

Bivand, R S and Rundel, C 2016 *Interface to Geometry Engine – Open Source (GEOS). R-packages 'rgeos'*. Available at https://cran.r-project.org/web/packages/rgeos/ [Last accessed 10 August 2018].

Bivand, R S, Pebesma, E and Gomez-Rubio, V 2013 *Applied spatial data analysis with R*. New York: Springer.

Brooks, R L 1986 *Catchment Analysis revisited: A Critique and Application of a Test Case*. Unpublished thesis (PhD), University of Kentucky.

Cappenberg, K 2014 Landscape as a Feature: Using GIS and Statistics to Compare Two Types of Early Neolithic Sites in Lesser Poland. In: Kienlin, T L, Valde-Nowak, P, Korczyńska, M, Cappenberg, K, and Ociepka, J (eds.) *Settlement, communication and exchange around the Western Carpathians: International Workshop held at the Institute of Archaeology, Jagiellonian University, Kraków, October 27–28th, 2012*. Oxford: Archaeopress, pp. 51–66.

Chrisholm, M 1968 *Rural Settlement and Land Use*. London: Hutchinson.

Christaller, W 1933 *Die zentralen Orte in Süddeutschland. Eine ökonomisch-geographische Untersuchung über die Gesetzmäßigkeit der Verbreitung und Entwicklung der Siedlungen mit städtischer Funktion*. Jena: Fischer.

Clarke, D L 1968 *Analytical Archaeology*. London: Methuen.

Davidson, I 1981 Can we study prehistoric economy for fisher-gatherer-hunters? - a historical approach to Cambridge „Palaeoeconomy". In: Sheridan, A and Bailey, G N (eds) *Economic archaeology: towards an integration of ecological and social approaches. British Archaeological Reports, International series 96*. Oxford: British Archaeological Reports, pp. 17–33.

van Etten, J 2015 *Distances and Routes on Geographical Grids. R-package 'gdistance'. Available at https://cran.r-project.org/web/packages/gdistance/* [Last accessed 10 August 2018].

**Farr, T G, Rosen, P A, Caro, E, Crippen, R, Duren, R, Hensley, S, Kobrick, M, Paller, M, Rodriguez, E, Roth, L, Seal, D, Shaffer, S, Shimada, J, Umland, J, Werner, M, Oskin, M, Burbank, D and

Alsdorf, D 2007 The Shuttle Radar Topography Mission. *Reviews of Geophysics,* 45(2): 1–33. DOI: 10.1029/2005RG000183

Findlow, F J and Ericson, J E 1980 Catchment analysis: essays on prehistoric resource space. *Anthropology UCLA 10*. Los Angeles: University of California.

Fleming, M D and Hoffer, R M 1979 Machine processing of landsat MSS data and DMA topographic data for forest cover type mapping. *LARS Technical Report*, 062879: 377–390.

Foley, R 1977 Space and Energy: A Method for Analysing Habitat Value and Utilization in Relation to Archaeological Sites. In: Clarke, D L (ed.) *Spatial Archaeology*. London: Academic Press, pp. 163–187.

Fries, J 2005 Methodische Überlegungen zur Ressource Boden. *Archäologische Informationen*, 28(1–2): 139–147.

Gesch, D, Oimoen, M, Zhang, Z, Meyer, D and Danielson, J 2012 Validation of the Aster Global DEM Version 2 over the conterminous United States. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIX–B4: 281–286. DOI: 10.5194/isprsarchives-XXXIX-B4-281-2012

Gilman, A and Thornes, J B 1985 *Land-use and prehistory in South-East Spain. The London Research Series in Geography 8*. London: Allen & Unwin.

Gorenflo, L J and Gale, N 1990 Mapping Regional Settlement in Information Space. *Journal of Anthropological Archaeology*, 9(1): 240–274. DOI: 10.1016/0278-4165(90)90008-2

Gorokhovich, Y and Voustianiouk, A 2006 Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. *Remote Sensing of Environment*, 104(4): 409–415. DOI: 10.1016/j.rse.2006.05.012

Gringmuth-Dallmer, E and Altermann, M 1985 Zum Boden als Standortfaktor ur- und frühgeschichtlicher Siedlungen. *Jahresschrift für mitteldeutsche Vorgeschichte*, 68: 339–355.

Guth, P L 1995 Slope and aspect calculations on gridded DEMs: examples from a geomorphometric toolbox for personal computers. *Zeitschrift für Geomorphologie, Neue Folge, Supplement Band*, 101: 31–52.

Henkner, J, Ahlrichs, J, Downey, S, Fuchs, M, James, B, Knopf, T, Scholten, T, Teuber, S and Kühn, P 2017 Archaeopedological analyses of colluvium: a proxy for regional land use history in southwest Germany. *CATENA*, 155: 93–113. DOI: 10.1016/j.catena.2017.03.005

Henkner, J, Ahlrichs, J, Fischer, E, Fuchs, M, Knopf, T Rösch, M, Scholten, T and Kühn, P 2018a Land use dynamics derived from colluvial deposits and bogs in the Black Forest, Germany. *Journal of Plant Nutrition and Soil Science*, 181(2): 240–260. DOI:10.1002/jpln.201700249

Henkner, J, Ahlrichs, J, Downey, S, Fuchs, M, James, B, Junge, A, Knopf, T, Scholten, T and Kühn, P 2018b Archaeopedological analysis of colluvial deposits in favourable and unfavourable areas: reconstruction of land use dynamics in SW Germany. *Royal Society Open Science*. DOI: 10.1098/rsos.171624

Henry, D O, Belmaker, M and Bergin, S M 2017 The effect of terrain on Neanderthal ecology in the Levant. *Quaternary International*, 435: 94–105. DOI: 10.1016/j.quaint.2015.10.023

Herzog, I 2013 The Potential and Limits of Optimal Path Analysis. In: Bevan, A and Lake, M (eds.) *Computational Approaches to Archaeological Spaces*. Walnut Creek, California: Left Coast Press.

Herzog, I 2014 A review of case studies in archaeological least-cost analysis. *Archaeologia e Calcolatori*, 25(1): 223–239.

Hesse, R 2012 Using lidar-derived Local Relief Models (lrm) as a new tool for archaeological prospection. In: Kluiving, S J and Guttmann-Bond, E B (eds.) *Landscape Archaeology between Art and Science. From a Multi- to an Interdisciplinary Approach*. Amsterdam: Amsterdam University Press, pp. 369–378.

Higgs, E S 1972 *Papers in Economic Prehistory. Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Higgs, E S 1975 *Palaeoeconomy: being the second volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Higgs, E S and Jarman, M R 1969 The origins of agriculture: a reconsideration. *Antiquity*, 43(1): 31–41. DOI: 10.1017/S0003598X00039958

Higgs, E S and Vita-Finzi, C 1972 Prehistoric economies: a territorial approach. In: Higgs, E S (ed.) *Papers in Economic Prehistory. Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press, pp. 27–38.

Higgs, E S and Jarman, M R 1975 Palaeoeconomy. In: Higgs, E S (ed.) *Palaeoeconomy: being the second volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press, pp. 1–7.

Higgs, E S and Vita-Finzi, C 1966 The Climate, Environment and Industries of Stone Age Greece: Part II. *Proceedings of the Prehistoric Society*, 32(1): 1–29.

Higgs, E S, Vita-Finzi, C, Harris, D R, Fagg, A E and Bottema, S 1967 The Climate, Environment and Industries of Stone Age Greece: Part III. *Proceedings of the Prehistoric Society*, 33(1): 1–29.

Hijmans, R J 2016 *Geographic Data Analysis and Modeling. R-package 'raster'. Available at https://cran.r-project.org/web/packages/raster/ [Last accessed 10 August 2018].*

Horn, B K P 1981 Hillshading and the reflectance map. *Proceedings of IEEE*, 69(1): 14–47. DOI: 0018-9219/81/0100-0014$00.75.

Hunt, E A 1992 Upgrading Site-Catchment Analyses with the Use of GIS: Investigating the Settlement Patterns of Horticulturalists. *World Archaeology*, 24(2): 283–309.

Imhof, E 1950 *Gelände und Karte*. Zürich: Rentsch.

Jarman, M R 1972 A territorial model for archaeology: a behavioral and geographical approach. In: Clarke, D L (ed.) *Models in Archaeology*. London: Methuen, pp. 705–733.

Jarman, M R 1976 Prehistoric economic development in sub-Alpine Italy. In: Sieveking, G de G, Longworth, I H and Wilson, K E (eds.) *Problems in Economic and Social Archaeology*. London: Duckworth, pp. 523–548.

Jarman, M R, Vita-Finzi, C and Higgs, E S 1972 Site catchment analysis in archaeology. In: Ucko, P J (ed.) *Man, settlement and urbanism: proceedings of a meeting of the research seminar in archaeology and related subjects held at the institute of archaeology*. Gloucester Crescent: Duckworth, pp. 61–66.

Jarman, M R, Bailey, G N and Jarman, H N 1982 *Early european Agriculture. Its foundation and development: being the third volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Jarvis, A, Reuter, H I, Nelson, A and Guevara, E 2008 *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Available at http://srtm.csi.cgiar.org [Last accessed 10 August 2018].

Jochim, M A 1976 *Hunter-Gatherer Subsistence and Settlement: A Predictive Model*. New York: Academic Press.

Keydel, W, Hounam, D and Werner, M 2000 *X-SAR/SRTM: Part of a Global Earth Mapping Mission. Paper presented at the RTO SET Symposium on "Space-Based Observation Technology", held on the Island of Samos, Greece, 16-18 October 2000, and published in RTO MP-61.* Available at https://www.dtic.mil/dtic/tr/fulltext/u2/p010830.pdf [Last accessed 10 August 2018].

Knopf, T and Ahlrichs, J J 2017 Der Magdalenenberg in Raum und Zeit. *Archäologische Informationen aus Baden-Württemberg*, 77: 52–65.

Lee, R B 1969 Kung bushmen subsistence: An input-output analysis. In: Vayda, A P (ed.). *Environment and cultural behaviour: Ecological studies in Cultural Anthropology*. New York: Natural History Press, pp. 47–79.

Li, P, Shi, C, Li, Z, Müller, J-P, Drummond, J, Li, X, Li, T, Li, Y and Liu, J 2012 Evaluation of Aster GDEM Ver2 using GPS Measurements and SRTM Ver4.1 in China. *Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 1–4: 181–186. DOI: 10.5194/isprsannals-I-4-181-2012

Ludwig, R and Schneider, P 2006 Validation of DEMs from SRTM X-SAR for applications in hydrologic modeling. *ISPRS Journal of Photogrammetry & Remote Sensing*, 60: 339–358. DOI: 10.1016/j.isprsjprs.2006.05.003

Miera, J J 2020 Ur- und frühgeschichtliche Siedlungsdynamiken zwischen Gunst- und Ungunsträumen in Südwestdeutschland – Landschaftsarchäologische Untersuchungen zur Baar und den angrenzenden Naturräumen des Schwarzwaldes und der Schwäbischen Alb. *RessourcenKulturen* 10. Tübingen: Tübingen University Press. DOI: 10.15496/publikation-45820

Miera, J J, Henkner, J, Schmidt, K, Fuchs, M, Scholten, T, Kühn, P and Knopf, T 2019 Neolithic settlement dynamics derived from archaeological data and colluvial deposits between the Baar region and the adjacent low mountain ranges, southwest Germany. *E&G Quaternary Science Journal*, 68: 75–93. DOI: 10.5194/egqsj-68-75-2019

Miera, J J, Schmidt, K, von Suchodoletz, H, Ulrich, M, Werther, L, Zielhofer, C, Ettel, P, Veit, U 2022

Large-scale investigations of Neolithic settlement dynamics in Central Germany based on machine learning analysis: a case study from the Weiße Elster river catchment. *PLoS ONE*, 17(4): e0265835. DOI: 10.1371/journal.pone.0265835

Mytum, H C 1988 On-site and Off-site Evidence for Changes in Subsistence Economy: Iron Age and Romano-British West Wales. In: Bintliff, J L, Davidson, D A and Grant, E G (eds) *Conceptual Issues in Environmental Archaeology*. Edinburgh: University Press, pp. 72–81.

Paetzold, D 1992 Bemerkungen zum Siedlungsverhalten neolithischer bis latènezeitlicher Bevölkerungen zwischen Regensburg und Deggendorf. Gab es Besiedlungsschwerpunkte in Abhängigkeit von naturräumlicher Gliederung und Bodenbeschaffenheit? *Bayerische Vorgeschichtsblätter*, 57: 77–102.

Pebesma, E J 2004 Multivariable geostatistics in S: the gstat package. *Computers & Geosciences*, 30(1): 683–691.

Pebesma, E J and Bivand, R S 2005 *Classes and methods for spatial data in R. R News* 5(2). Available at http://cran.r-project.org/doc/Rnews/ [Last accessed 10 August 2018].

Purinton, B and Bookhagen, B 2017 Validation of DEMs (DEMs) and comparison of geomorphic metrics on the southern Central Andean Plateau. *Earth Surface Dynamics*, 5(1): 211–237. DOI: 10.5194/esurf-5-211-2017

Rabus, B, Eineder, M, Roth, A and Bamler, R 2003 The shuttle radar topography mission — a new class of DEMs acquired by spaceborne radar. *ISPRS Journal of Photogrammetry & Remote Sensing*, 57: 241–262. DOI: 10.1016/S0924-2716(02)00124-7

Ritter, P 1987 A vector-based slope and aspect generation algorithm. *Photogrammetric Engineering and Remote Sensing*, 53(1): 1109–1111.

Rodriguez, E, Morris, C S, Belz, J E, Chapin, E C, Martin, J M, Daffer, W and Hensley, S 2005 *An assessment of the SRTM topographic products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California.* Available at http://www2.jpl.nasa.gov/srtm/srtmBibliography.html [Last accessed 10 August 2018].

Rogers, S R, Collet, C and Lugon, R 2014 Least cost path analysis for predicting glacial archaeological site potential in central Europe. In: Traviglia, A (ed.) *Across Space and Time. Computer Applications and Quantitative Methods in Archaeology (CAA), Proceedings of the 41st International Conference (Perth, Australia, March 25–28, 2013)*. Amsterdam: Amsterdam University Press.

Rogers, S R, Fisher, M and Huss, M 2014 Combining glaciological and archaeological methods for gauging glacial archaeological potential. *Journal of Archaeological Science*, 52, pp. 410–420. DOI: 10.1016/j.jas.2014.09.010

Roper, D C 1979 The Method and Theory of Site Catchment Analysis: A Review. *Advances in Archaeological Method and Theory*, 2(1): 119–140.

Roubis, D, Sogliani, F, Gabellone, F, Danese, M and Gnesi, D 2011 Archaeological Landscapes through GIS (Cost Surface Analysis) and Virtual Reality: A Case Study on the Monastic Site of Jure Vetere (Calabria, Italy). In: Jerem, E, Redö, F and Szeverényi, V (eds) *On the Road to Reconstructing the Past. Computer Applications and Quantative Methods in Archaeology (CAA). Proceedings of the 36th CAA Conference, Budapest, 2–6th April 2008*. Budapest: Archaeolingua Foundation, pp. 476–484.

Sarkar, D 2008 *Lattice: Multivariate Data Visualization with R.* New York: Springer.

Thomson, D F 1939 The seasonal factor in human culture. *Proceedings of the Prehistoric Society*, 5(1): 209–221. DOI: 10.1017/S0079497X00020545

von Thünen, J H 1826 *Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie, oder Untersuchungen über den Einfluss, den die Getreidepreise, der Reichthum des Bodens und die Abgaben auf den Ackerbau ausüben*. Hamburg: Perthes.

Tobler, W R 1961 *Map transformation of geographic space.* Unpublished thesis (PhD), University of Washington.

Tobler, W R 1993 *Three presentations on geographical analysis and modelling: non-isotrophic modelling, speculations on the geometry of geography, global spatial analysis. National Center for Geographic Information and Analysis. Technical Report* 93–1. Available at https://escholarship.org/uc/item/05r820mz [Last accessed 10 August 2018].

Tschauner, H 1996 Middle-range theory, behavioural archaeology, and post-empiricist philosophy of science in archaeology. *Journal of Archaeological Method and Theory*, 3(1): 1–30.

Tiffany, J A and Abbott, L R 1982 Site Catchment Analysis: Application to Iowa Archaeology. *Journal of Field Archaeology*, 9(1): 313–322. DOI: 10.1179/009346982791504634

Trigger, B G 1995 Expanding middle-range theory. *Antiquity*, 69(294): 449–458. DOI: 10.1017/S0003598X00081862

Trigger, B G 2008 *A History of Archaeological Thought*. Cambridge: Cambridge University Press.

Uthmeier, T, Ickler, S and Kurbjuhn, M 2008 Site catchment Analysis in the Late Crimea Middle Palaeolithic: a GIS Based Approach. In: Chabai, V P, Richter, J and Uthmeier, T (eds) *Kabazi V: Interstratification of Micoquian and Levallois-Mousterian campsites, Part II*. Simferopol: National Academy of Sciences of Ukraine, pp. 481–508.

Valde-Nowak, P 2002 *Siedlungsarchäologische Untersuchungen zur neolithischen Nutzung der mitteleuropäischen Gebirgslandschaften. Internationale Archäologie 69.* Rahden: M. Leidorf.

Vita-Finzi, C and Higgs, E S 1970 Prehistoric Economy in the Mount Carmel Area of Palestine: Site Catchment Analysis. With Contributions by Sturdy, D, Harriss, J, Legge, A J, Tippett, H. *Proceedings of the Prehistoric Society*, 36(1): 1–37. DOI: 10.1017/S0079497X00013074

Zevenbergen. L W and Thorne, C R 1987 Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, 12(1): 47–56. DOI: 10.1002/esp.3290120107

Zipf, G R 1965 *Human Behavior and the Principle of Least Effort*. New York: Hafner.

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Espen Uleberg & Mieko Matsumoto
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Strange Attractors in the Norwegian Stone Age

Espen Uleberg
Museum of Cultural History
University of Oslo
espen.uleberg@khm.uio.no

Mieko Matsumoto
Museum of Cultural History
University of Oslo
mieko.matsumoto@khm.uio.no

Abstract

This paper explores an application of concepts from chaos theory and nonlinear system theory, and argues that nonlinear system theory is a useful tool in understanding the use of landscape and the creation of taskscapes by prehistoric and modern people around Lake Vavatn in Lærdalsfjellene (the Lærdal Mountains), a part of the high mountains in South Norway. It is necessary to replace a static model based on duration and stability with a model that can focus on change and variability in recorded archaeological material that is the result of past and present events. Sites and areas that have artefacts indicating many events are seen as focal points in the landscape. The trajectories of movements and events in time and space are described as strange attractors. These strange attractors are visualised through the Poincaré set created by sites and single artefacts. In the case of Lake Vavatn, traces of human activity from several periods have created points in the Poincaré set; the typologically dated stone artefacts from earliest Middle Mesolithic at several early intervals, possible pastoralist activities from the Neolithic, the probably medieval animal fall pits at a later time, the modern shieling, cottages for leisure, and archaeological surveying today. The sum of observations does not allow statements about continuation during this over 8000-year period of archaeological and modern history, but it does show that Lake Vavatn has been attractive throughout multiple periods.

Keywords: Chaos theory, strange attractor, Lærdalsfjellene, Lake Vavatn, MUSITark

Introduction

This paper will explore an application of concepts from chaos theory and nonlinear system theory in relation to the distribution of traces of human activities in the high mountains in South Norway. Archaeological artefacts found in the landscape are remains of past activities registered through modern archaeological activity. These activities take place in a four-dimensional phase-space, consisting of the three-dimensional landscape and the fourth dimension time. The activities are a range of tasks of shorter and longer duration. It is events of shorter duration, like hunting and butchering, where flint knapping to produce elaborate or expedient tools can be even more ephemeral events prior to or during a hunt. It is also events of longer duration like a year cycle consisting of movement coast-inland, and finally events belonging to archaeological survey or other activity that leads to the discovery of archaeological artefacts. All these activities can be cycles of shorter or longer duration, and create taskscapes that people relate to (Ingold 1993). This is a chaotic system, a system of stochastic determinism. The performance of the activities follow trajectories that describe the system — the system's strange attractor. The strange attractor cannot be described directly, as the distribution in time is gone. However, the remains of the prehistoric activities are now found in the three-dimensional landscape forming a Poincaré set that describe the system indirectly.

The paper uses material from the national MUSIT database, which is published as open data.

The Norwegian university museums have since the early 1990s cooperated to create common database solutions for the archaeological collections in Norway (Matsumoto & Uleberg 2015; Ore 1998). This cooperation has been organised in MUSIT (MUSeumIT) since 2007. As of October 2019 more than 1.4 million georeferenced entries are published online as open data.[1] The dataset consists of converted artefact catalogues from 1829 until 2002. After a transient period until 2004, all catalogues are entered in the MUSIT artefact database, archaeology (MUSITark). The earlier catalogues are written to give an easily readable overview of the artefacts. The more recent catalogues are entered with detailed context information, which makes it possible to conduct site analyses directly. The museums also publish photos of artefacts and from sites with a CC BY-SA 4.0 licence.[2] This way of publishing archaeological artefacts opens new venues for archaeological research in Norway. The material used in this paper is exclusively taken from MUSITark.

Stone Age Sites in the High Mountains

The major part of the known Stone Age sites in the high mountains in Norway has been found during archaeological surveys for construction of hydroelectric dams. This work started in the late 1950s and continues even today as renewed surveys at existing constructions (Indrelid 2006). In some areas, like around Lake Vavatn that we will discuss later, essential knowledge also comes from private initiatives. All in all this provides an extensive knowledge base for Stone Age sites in the Norwegian high mountains.

Groups of hunter-gatherers came to the high mountains shortly after the end of the Last Ice Age (ca 10 000 BP). The following warm periods made it possible for trees to grow at a much higher altitude than today. The high forest limit probably continued until the beginning of the Iron Age / the climatic Sub-Atlantic period. The existence of a birch belt above the deciduous forest can be found in pollen analysis and especially macrofossils like tree trunks at high altitudes (Faarlund & Aas 1991). This implies that today's high mountain sites were mainly in forested areas.

The oldest mountain sites in South Norway are found at Store Fløyrlivatnet (Figure 1: 7), where five sites are dated to the interval between 9750 ± 80 and 9360 ± 80 BP. Analyses of the charcoal show that the vegetation consisted of birch and willow. Pieces of oak and pine from this early stage indicate that wooden objects have been brought from the coast to the mountain sites, probably reflecting seasonal movements between coast and inland (Bang-Andersen 2000: 27–32). The fact that there are Early Mesolithic sites both at the coast and in the inland in Western Norway indicates that the pioneers were not specialised, neither as reindeer hunters nor with a marine adaptation (Persson 2017: 207).

The earliest sites in Lærdalsfjellene (Figure 1:1–6), the area we will concentrate on here, are dated to around 8500 BP. Organic material like bone and charcoal are rarely found, as at other Norwegian Stone Age sites, and consequently the sites are often only typologically dated. It is also rare to find sites with stratigraphy, since they are mainly open-air sites with artefacts in or directly below a thin layer of turf. Sites in Lærdalsfjellene can have material ranging from Early Mesolithic to Late Neolithic (Matsumoto & Uleberg 2002; Uleberg 2002; Uleberg 2003; Uleberg 2004), and the site Hein 33 at Halnefjorden in Hardangervidda is reported to have at least six different visits over a span of almost 4000 years (Indrelid 1994: 218).

Major traditional research foci related to the high mountain Stone Age has been seasonal movement and site continuity (Johansen 1978; Mikkelsen 1989). The models, especially in Arne B. Johansen's studies of Lærdalsfjellene in the 1970s, have underlined the stability in these systems, with the same annual cycle continuing throughout millennia (Johansen 1970; Johansen 1978). A hiatus in the utilisation of the high mountains after 6000 BC has been explained by climate deterioration (Moe, Indrelid & Kjos-Hanssen 1978). A climate change would have given worse conditions for the reindeer and consequently fewer sites. This has later been described as a "classic hiatus" (Selsing 2010: 162 ff.), but has also been criticised as it could be a result of skewed sampling. Per Persson

1 http://www.unimus.no/portal/
2 https://creativecommons.org/

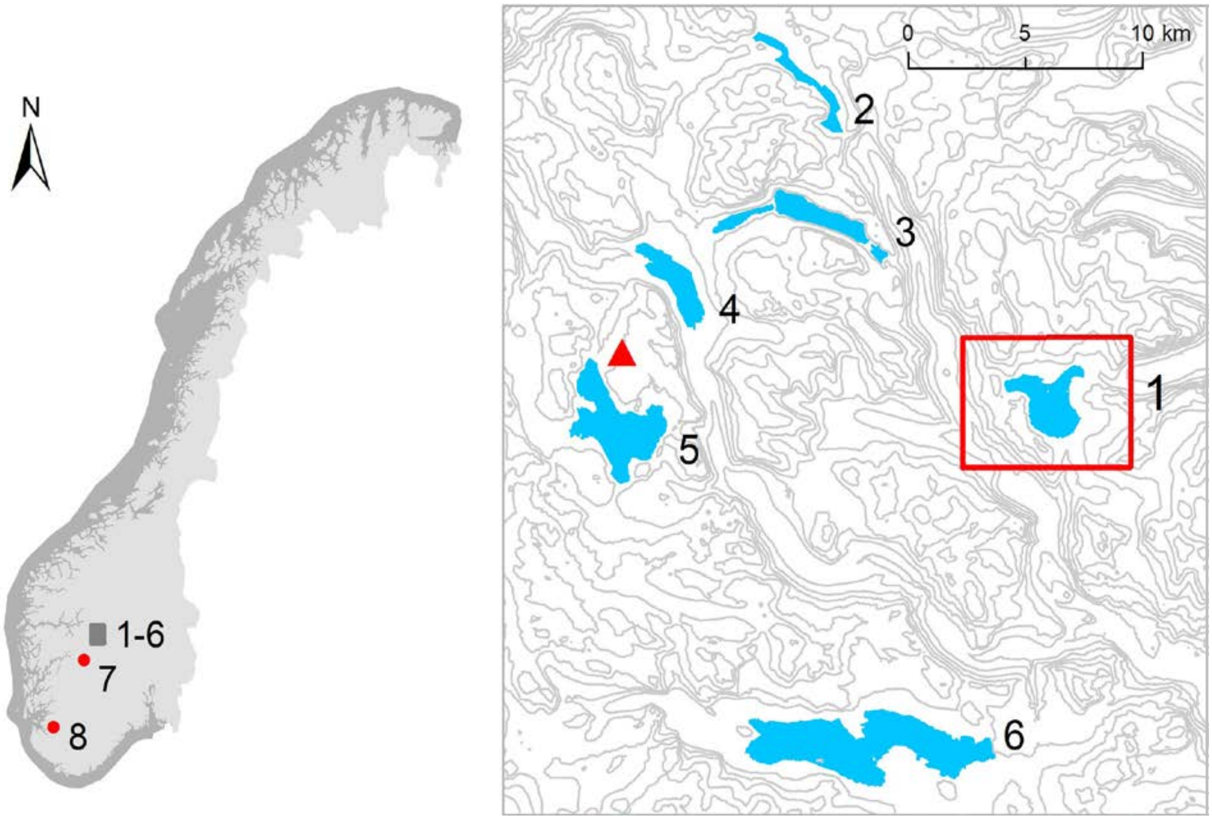

Figure 1. Major lakes (1-6) in Lærdalsfjellene, Hein 33 at Halnefjorden (7) in Hardangervidda, and Store Fløyrlivatnet (8) in Rogaland. 1. Vavatn, 2. Sulevatnet, 3. Juklevatnet, 4. Eldrevatnet, 5. Øljusjøen, 6. Gyrinosvatnet/Flævatn. ▲Kjølskarvet quartzite quarry. Contour interval is 100 m. Red frame indicates Lake Vavatn and surroundings shown in Fig. 5.

suggests this hiatus could mark the end of an Early Mesolithic pioneer phase (Persson 2017: 200).

Two periods of inland activity during the Mesolithic have been demonstrated by Joel Boaz (1998) based on radiocarbon dating and typology. This pattern has recently been substantiated by new sets of radiocarbon dating on osteological material. They indicate a period of less use of the inland regions after 8500 BC, and a renewed higher interest in the interior lowland areas from around 6900 BC (Persson 2017: 210).

However, the site distribution can be indications of more fluctuation and serves as a good example of a non-linear system where the stability is interrupted by exogenous or endogenous factors, passing through a period of instability and then finding a new, relatively steady state.

Reindeer hunting continues to be the focus for the understanding of site distribution in the high mountains. There are two reasons why this cannot be the only explanation through all of the Stone Age. One reason is that the higher forest limit will have influenced the reindeer trails and the species that could be hunted. A higher forest limit will give better conditions for moose, and moose bones have been found at a site 1130 m a.s.l. at Hardangervidda (Indrelid 1994: 37, 236–241). The other reason is that Neolithic sites tend to covariate with the Iron Age and modern sites used for shieling. This can indicate that such a place in the landscape was chosen on basis of the interests of pastoralists and not hunters (Meløe 1989; Prescott 1995).

The sites in the high mountains are generally found around the lakes. The obvious reason is that the surveys were concentrated in areas inflicted by dam constructions. Some sites are spatially quite concentrated and well-defined, but in other cases archaeological material can be found along shoreline stretches. In the latter case, it could be more useful to describe this as continuous activity areas with remains from separate activities (events) taking place at shorter or longer, continuous or separated time intervals. In the frame of chaos theory and strange attractors, each artefact will be a point in the Poincaré set.

Stability and Change—
Movement in the Landscape

The archaeological material is the source to understand the prehistoric landscape as experienced and created by humans. The quest for the landscapes of past people will start at the recorded landscape, move on to the reconstructed landscape, then on to the utopian landscape, and finally try to reach the experienced landscape (Welinder 1988: 50–53). The recorded landscape is the site distribution map, the results of surveys enriched with more knowledge about the excavated sites, but where humans are anonymous groups leaving artefacts at certain points in the landscape. This recorded landscape is transformed into the reconstructed landscape through pollen analysis and other methods to reconstruct the environment. In systems theory this has often been presented as a site-catchment analysis, where the site is the centre of a certain form of subsistence maintained by optimising groups. The utopian landscape catches the movement between the larger sites, and the series of events that happened between these sites. It is not possible to document all traces in the landscape, but the smaller off-site artefact clusters and single finds shed some light on the activities. All these landscapes are the landscapes of the researchers. The experienced landscape belongs only to the people living in it and re-creating it every day through acting and sharing experiences. The experienced landscape eludes us, and we can never really understand it fully.

The flow and continuous activity that Stig Welinder describes as the utopian landscape can to a certain extent be approached by using chaîne opératoire. The research method chaîne opératoire concentrates on the sequence of prehistoric human actions. These actions can be in one place over a short time span, like the production of tools. Chaîne opératoire can however also be used in a wider context, over longer periods and larger areas. It can describe movement through the landscape with a series of repeating actions at different places (Conneler 2006). Chaîne opératoire targets these events in themselves. Tim Ingold's taskscape (Ingold 1993) focuses on how these events let the actors create their own landscape and in this way approaches Welinder's experienced landscape. Groups with different subsistence patterns will observe and be conscious about different aspects of the landscape (Meløe 1989). Their perception of the landscape is dependent on their actions, which again are connected to their mode of subsistence. A hunter-gatherer will be aware of other qualitative aspects than a pastoralist. Hunter-gatherers will look for animal trails and think of how to hunt. Pastoralists will look for areas well suited for herding and grazing and think of how to protect their animals. In a similar way, archaeologists will look for places suitable for prehistoric events. Sites are registered where modern events of surveying coincides with prehistoric choices (cf. Fig. 6).

The chaîne opératoire behind certain tools and artefacts can be demonstrated by conjoining the remaining pieces. The conjoining can illustrate movement at a site; that different work sequences have been performed at different places. Conjoining can also show traces of movement in the landscape. An example of this can be found at the Lake Gyrinosvatn (Figure 1: 6), only 20 km South-West from Lake Vavatn. There are several excavated sites around Lake Gyrinosvatn with the characteristic local greenish quartzite known as Lærdalskvartsitt, and it has been possible to put together pieces from several of these. This shows that nodules have been taken from one site and brought to another to be used further (Schaller-Åhrberg 1990). This example is intriguing especially because neither the nodule nor the other pieces can be dated with any certainty. It is therefore not possible to know whether it is the same person who used this nodule or whether the nodule was left at one site and picked up again shortly or several years later. In this way there is a continuity and connection not only through space but possibly also through a vast timespan.

Movement in the landscape can also be inferred from the use of quartzite outcrops. Quartzite nodules can be found several places in Lærdalsfjellene, but there are also several quartzite outcrops known to have been used during the Stone Age and Bronze Age.

Quarries

The most prominent quartzite quarry in Lærdalsfjellene is at Kjølskarvet (Figure 1: ▲). The quartzite found here is an easily recognizable greenish type of Lærdalskvartsitt. Kjølskarvet is a promontory in a landscape without vegetation (Figure 2). The top is well above 1400 m a.s.l. and it has therefore always been above the local tree limit. There are also several smaller quarries close to the main site. Numerous activity areas are scattered in the vicinity and along the possible routes to and from the quarry. Arne B. Johansen's publication (1978) shows a model of the quarry with survey transects and areas with artefacts (Figure 3). Today we can see this as an illustration of a series of single events; the prehistoric distribution in time is not visible and the archaeological survey intersects the Poincaré set formed by the Stone Age artefacts.

Astrid J. Nyland's study of Stone Age and Bronze Age quarries in South Norway ranks Kjølskarvet as a lithic extraction site with a high level of activity. It is in use from the Middle Mesolithic to the Pre-Roman Iron Age, with lower activity in the first and last part of this long period. It is estimated that 100 m3 were extracted over a period of 8000 years (Nyland 2017a; Nyland 2017b).

Figure 2. Kjølskarvet, Quarry II, Lærdal, Sogn and Fjordane County. Photo: Arne B. Johansen. CC BY-SA 4.0.

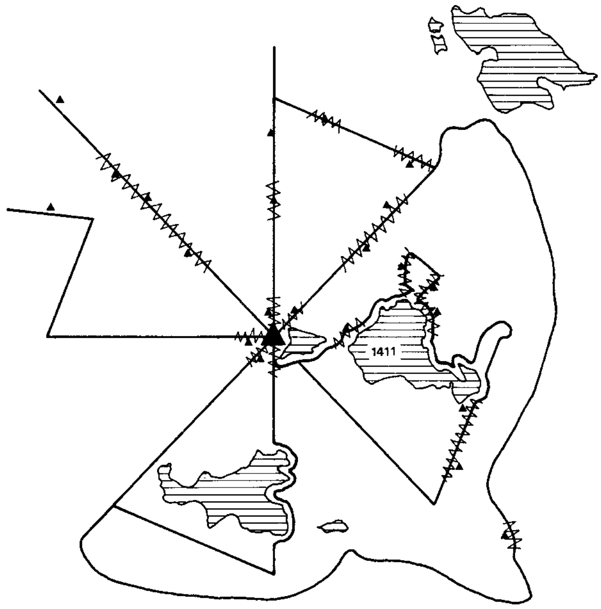

Figure 3. A schematic presentation of the survey around Kjølskarvet quartzite quarry. Trajectories show the lines of survey centripetally from the quarry, and scatters of artefact distributions are depicted where the survey event coincides with a prehistoric event. artefact, trajectory, ▲ quartzite quarry. North upwards (after Johansen 1978: 74).

Chaos Theory and the Human Trajectory in the Landscape

There was a high interest in chaos theory through the 1980s. James Gleick's book entitled Chaos. Making a New Science (1987) introduced a wide audience to the idea of random determinism. The most well-known concept connected to chaos theory is "the butterfly effect", which refers to the sensitive dependence on minor variations in initial conditions that can have large consequences in a later state. This term was coined approximately one and a half centuries earlier by the American mathematician and meteorologist Edward Norton Lorenz. He noticed that small variations in the initial conditions in his weather models would give large variations. The "butterfly effect" demonstrates this by saying that a butterfly flapping its wings can lead to a tornado at another location several days later (Gleick 1987). An important point is the contrast to traditional system theory. Linear system theory will see minor variations as noise that should be filtered away, but nonlinear system theory, and especially chaos theory, can focus on small variations and events that lead to great changes. An example from anthropology could be the introduction of steel axes to the aborigine Yir Yoront group in Australia. Axes could suddenly be owned not only by older men but also by women and younger men, and this in turn uprooted the traditional relations between older men and the other members of the society (Sharp 1952). An example from Scandinavian archaeology could be the transition from the Mesolithic to the Neolithic in Denmark. The transition period was very short, only some 50 years. This indicates a total shift from one system to another. The old system, the Mesolithic way of life, collapsed, and it has been suggested that catastrophe theory could

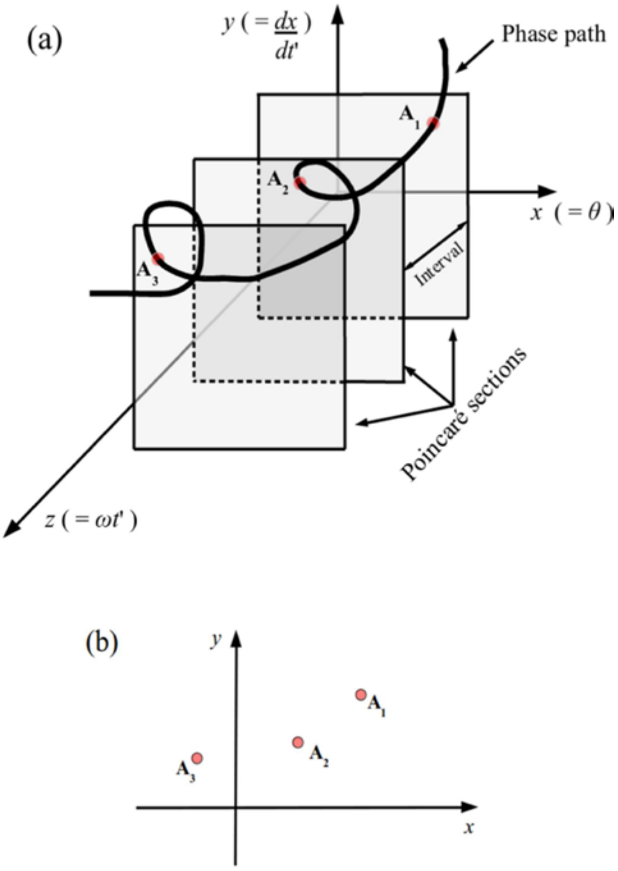

Figure 4. Poincaré's phase space diagrams. Parallel planes (a) showing sections through the motion, with crossing points A1, A2, A3, which are projected on the 2D plane (b) (Cattani et al. 2017: figure 4).

be used as a model to explain this; a catastrophe that leads to the total breakdown of the system (Madsen 1987; Madsen 1988). However, explaining a sudden change like this by chaos theory would imply that the system continues, but enters another steady state.

In 1986, The Royal Society in London defined chaos as stochastic behaviour in a deterministic system (Stewart 2002: 17). Although there are a set of rules for how a system develops, the system can go from a steady state to chaos and to a new steady state. It is an inherent aspect of the system that it can shift from one state to another without any external impact. This is consistent with Luhmann's theory of autopoiesis — self-referencing systems. A self-referencing system is self-contained, thus it does not need input from other systems. A self-referencing system can also contain mechanisms that allow it to change states — it can go from a steady state to chaos and return to another steady state (Luhmann 1992).

Chaos theory was introduced in Scandinavian archaeology in 1989/90 with a discussion in the periodical META (Welinder 1989; Wienberg 1989a; Wienberg 1989b). This discussion inspired a paper that suggested that chaos theory could be used to explain the sudden shift from a Mesolithic to a Neolithic subsistence by focusing on small changes (Welinder 1991: 245–247). Kristina Jennbert's theory that gift exchange is the main reason for the shift to a Neolithic economy (Jennbert 1984) could be seen as such a small change that has large consequences.

Traditional system theory is a useful concept to outline models and gives new insight in past cultures. Cultures can be in equilibrium in the way that, at certain scales, they can act as static systems; the same subsistence patterns are repeated over centuries. With this approach, erratic changes will be seen as disturbing noise that can be disregarded. However, such a model can be over-simplifying. Some of the most interesting aspects might not be taken into account, how humans have responded to change, for example — not only slow changes over time, but also sudden environmental changes or simply fresh ideas. New ideas are not necessarily due to external influences but can also be internal and can lead to a total disruption of an existing order.

In this way, nonlinear system theory allows a different approach to systems that cannot be described with traditional systems theory. Suzanne M. Spencer-Wood argues convincingly that culture can be treated as a nonlinear system. Her arguments focuses on that culture is a nonlinear system because it is complex, dissipative, and self-organising, and that culture is a chaotic system because it is sensitive to initial conditions, irreversible, and has an evolutionary path that cannot be accurately predicted (Spencer-Wood 2013: 6-7).

All possible states of a system are contained in the system's phase space. Within the phase space, regular systems will converge to a steady state. One example of a simple, regular system is the pendulum, where the steady state will be a point. The state the system converges to can be called an attractor, and in case of the pendulum, the attractor is periodic. More complex systems can have an attractor like a circle or a torus, but it will still be a stable attractor that can be predicted. The nature of the nonlinear system is such that the attractor cannot be predicted, because of its reliance on initial conditions. The set of equations describing the system can be fairly simple, but the development can be unpredictable. However, the system can be described through describing its attractor. Such a non-periodic attractor is called a strange attractor.

A strange attractor in an m-dimensional hyperspace can be described by observing it, but in some cases it is not possible to observe the attractor directly. A remaining option is to observe the attractor's Poincaré set. The Poincaré set is made up of points on an (m-1)-dimensional hyperplane through the m-dimensional phase space. The attractor is described by the points where the attractor passes through the hyperplane. This can be shown by drawing the movement as a time sequence. In Fig. 4, parallel planes illustrate stroboscopic sections of the motion, and the points A1, A2, A3 are where the strange attractor passes the hyperplane (Cattani et al. 2017).

The connection to the archaeological material is made by regarding sites in the landscape as points on a hyperplane. Describing activities and movement in the landscape (events) through this point scatter, is describing the attractor. Events take place in a 4D space-time hyperspace, and remain as points on the 3D landscape. In this way, all archaeological evidence, both larger sites, single artefacts within a site and stray finds, can be used at different scale levels in the same model to describe a flow of events. This is especially useful in a setting like the Norwegian high mountains where there is hardly any stratigraphy, and a concept like non-site archaeology could be more useful than to work with defined sites. Using Welinder's terms, the strange attractor is the utopian landscape, and the Poincaré set is the recorded landscape.

Each site and trace of prehistoric activity will, at different scale levels, be a point on the hyperplane. Areas with many events will have several points and can be recognised as magnet locations (Binford 1987: 26), or focal points. Such sites in the Norwegian high mountains are generally found at lakes, especially at river mouths, and often close to reindeer trails. As an example of a focal point, an area where several events have taken place in prehistory and the present, we will look more closely at the material from Lake Vavatn.

Lake Vavatn

The Lake Vavatn in Hemsedal is situated at 1124.5 m a.s.l. (Figure 5). It is one of a group of larger lakes with several Stone Age sites within a radius of 20 km; Sulevatnet, Juklevatnet, Eldrevatnet, Øljusjøen, and Gyrinosvatnet/Flævatn (Figure 1: 1–6). The lakes in this area are regulated for hydroelectric power, and there were extensive surveys in the 1960s as part of the investigations in Lærdalsfjellene (Johansen 1970; Johansen 1978; Schaller-Åhrberg 1990). Most of the lakes can therefore have a higher water level than earlier, but Lake Vavatn is regulated in the way that the water level can be lowered to as much as 8 m below normal height.

The lake was surveyed in the 1960s, but the first sites there were found much later: First as occasional finds and by a private initiative, and later through archaeological surveys (Matsumoto & Uleberg 2002). Several examples can show that repeated surveys by the same or different people will produce more sites (Indrelid 1994; Prescott 1995).

The sites around Lake Vavatn are concentrated around the northeastern bay of the lake, over a stretch of 2.4 km east–west and generally at a height between 1125 and 1140 m a.s.l. (Figure 5). The landscape in the west consists of relatively flat bogs closer to the water and moraine ridges on the hills up towards the high mountains. Further to the east, the terrain rises steeper from the lake. The shieling are placed on plateaus above a steep descent towards the lake. The terrain goes up to the top of Primstøyten 1179 m a.s.l. in the east, from where there is a good view over Lake Vavatn towards the west (Matsumoto & Uleberg 2002).

The site at Primstøyten is 170 m and one more site further southeast is almost 280 m from the lake. The view from the Primstøyten site over Lake Vavatn might indicate that it can be related to the other activities around the lake. Several of the finds have been made below normal water level. The richest sites are found close to the existing shieling and cottages at Fauskostølen. A short distance east of this there are animal fall pits and a reindeer trail coming down from the mountains to the north. There are also an animal fall pit in the northwest bay of the lake (Figure 5) (Matsumoto & Uleberg 2002).

The chronology for the sites around Lake Vavatn falls within a rather wide range between the Meso-

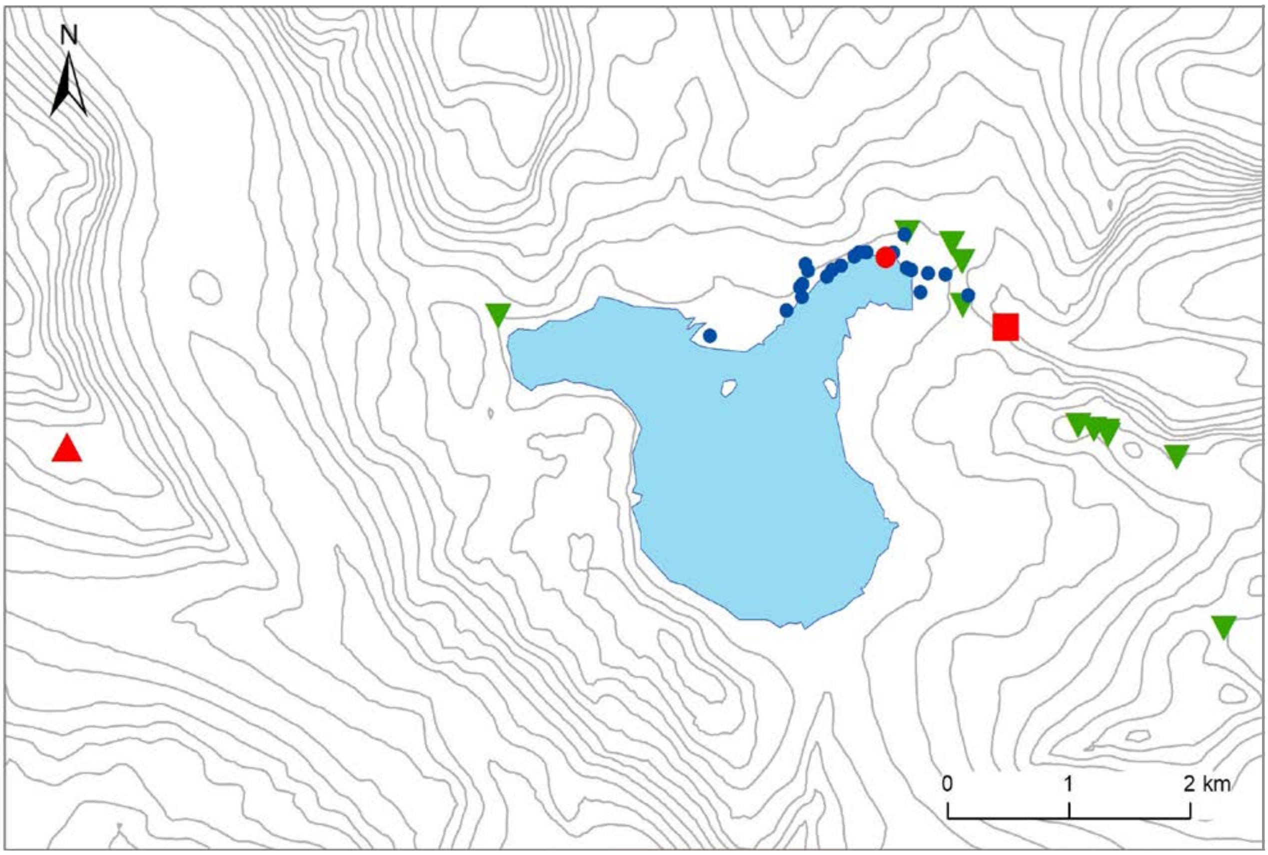

Figure 5. Lake Vavatn with •Stone Age sites and ● Fauskostølen along the north-eastern bay, and ■ Primstøyten to the east. a quartzite quarry to the west and ▼ animal fall pits Contour interval is 50 m. The Vabuleino area shown in Figure 6 is the NE part.

lithic Phase 2 and the Norwegian Bronze Age, in the period 6300–600 BC. All material is from surveys and surface collections, and the dating is based solely on typology. The finds at the largest site, Fauskostølen, are in an area covering 20 × 27 m; almost 20 m along the shore and 27 m down from the shieling and into the lake. The total weight of the finds from this site is 2.9 kg, of which 2.7 kg is quartz/quartzite tools and debitage. This site has also the only slate artefact known at Vavatn — a fragment of a Neolithic point. The relative composition of the major raw materials — quartz, quartzite, flint, and rock crystal — is the same as the total of all sites around the lake (Matsumoto & Uleberg 2002).

The north-eastern bay of Lake Vavatn was a focal point for movement and activities in the Stone Age, but activities were not as frequent here as around other lakes in Lærdalsfjellene (Figure 1). There are no indications that the repeated and occasional visits to the larger and smaller sites around Lake Vavatn were continuous; rather that periods of activity were separated by longer or shorter intervals. There has been a range of activities at Lake Vavatn. The activity during the Mesolithic will have been concentrated on hunting, as the lakes in Lærdalsfjellene are not known to be rich in fish (Johansen 1978). The animal fall pits close to the lake have not been dated, but the general dating of this kind of constructions in the high mountains are the Medieval Period, showing that the area has been used for hunting also in later periods. The character of the Neolithic occupation is not known in detail, but both hunting and shieling is possible. Modern activity is shieling and leisure, as there are several cottages close to the shieling. There is no reindeer hunting there today because the reindeer grazing in this area are domesticated.

Three types of modern activities at Lake Vavatn can be mentioned: The first, and oldest, is the pastoralism, as seen in the shieling. The second is leisure, connected to the cottages. The third is the archaeological survey. The fact that Lake Vavatn, especially the north-eastern bay area, was chosen for shieling, can indicate an understanding and reading of the landscape in common with Neolithic herders. Leisure activity in the high mountains starts in the 19th century, and a combination of these two event types triggered a renewed archaeological interest in Lake Vavatn. The third, and shortest, activity is the archaeological survey, where archaeologists aimed to read and understand the landscape in the way it was understood in prehistory. Sites are recorded where archaeologists and others find traces of prehistoric activity, or to phrase it differently; sites are found where reading of the landscape by archaeologists and prehistoric people results in activities at the same focal points in the landscape — the archaeologist digs at a place of a prehistoric event.

Past and Present in the Landscape

Spatial intersection of prehistoric and recent events can lead to increased knowledge of prehistory. Figure 6 depicts prehistoric and archaeological events leading to recognition of Stone Age activity, populating a Poincaré set. Plane A presents a hypothetical Stone Age sequence of movement and events. Places in the landscape where the activity left traces that can be found today is marked with blue points. Plane B presents a possible trajectory of an archaeologist surveying the area. The survey method is digging test pits, and test pits are marked with points. The grey points are test pits without finds, and the green are test pits with Stone Age artefacts. The red points in Plane C are the positive test pits in the real landscape. The trajectory in Plane A is one of the lines in the strange attractor of the Stone Age events at Lake Vavatn, and the red points in Plane C are the Poincaré set that virtually illustrates the strange attractor in the modern landscape.

Figure 6 is a simplified model that delineates the Poincaré set of only two hyperplanes — one representing Stone Age (oldest) actors and the other recent (newest). At Lake Vavatn, there are traces of other actors that can be plotted as points on several Poincaré sections. Densely populated Poincaré sections will give a good impression that the place is attractive. On the other hand, it is challenging to find a refined and suitable interval scale within the Stone Age to compare landscape utilisation at other lakes in Lærdalsfjellene. This is because Stone Age sites in the high mountains are the least datable, and therefore the most inspiring in an application of concepts from chaos theory and nonlinear system.

Conclusion

This paper argues that chaos theory and nonlinear system theory are a useful tool in understanding the use of landscape and the creation of taskscapes during the Stone Age in the Norwegian high mountains. It is necessary to replace a static model based on duration and stability with a model that can focus on change and variability. Small variations in the system can lead to total changes, and the system can change states, even independent of external influence.

The recorded archaeological material is the result of past and present events. As shown in Figure 6, a positive point on the map indicates a place where past and present understanding of a suitable site coincides. The mountain sites have in general no stratigraphy, and the artefacts can be picked up from the ground or be found in or just under the turf. This means that the once existing distribution in time is gone. One could describe it in the way that all events are projected onto the landscape parallel to the time axis and only the spatial distribution remains.

A continuation of this line of thought is to see the archaeological distribution as a Poincaré set. The Poincaré set describes the system by making the footprints of the attractor visible. The attractor is the trajectory of the events in time–space. The events are concentrating, recurring, at focal points, not because of a constant regularity, but because underlying factors attract attention to certain places. The sites at Lake Vavatn is one such place of importance.

The occupation at Lake Vavatn is of long duration. The first visitors at the sites arrived as hunters/gatherers, and animal fall pits shows later hunting activity close by. The places were later visited by pastoralists, and the tradition of bringing sheep and goats to Lake Vavatn for grazing during the summer continues even today. The sum of observations does not allow statements about continuation during this over 8000-year period of archaeological and modern history, but it does show that Lake Vavatn has been attractive throughout multiple periods. The typologically dated stone artefacts can point at several early

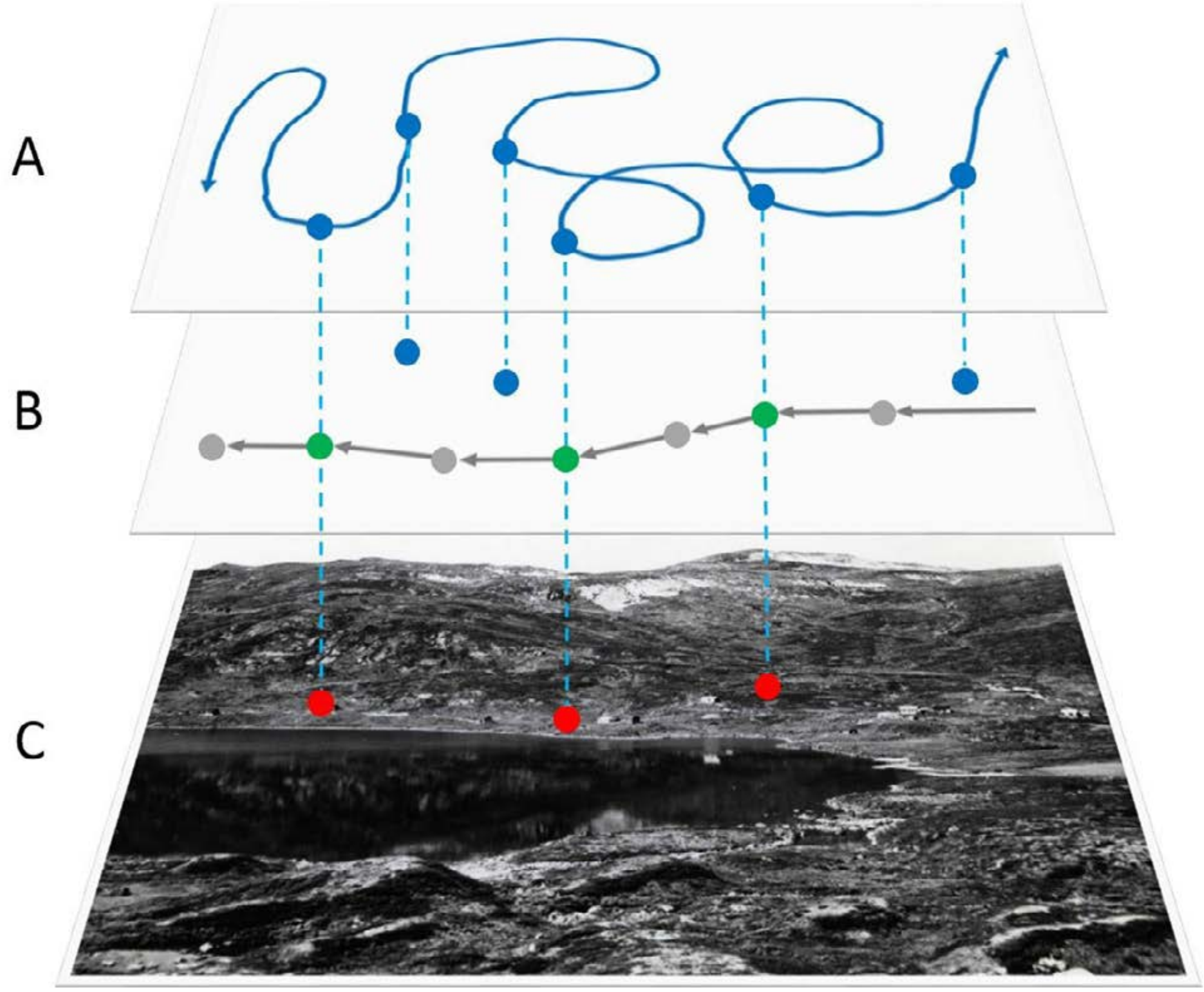

Figure 6. Schematic depiction of two Poincaré sets (prehistoric and present), with archaeological sites in a strange attractor projected on the real landscape. Plane A: Prehistoric path (trajectory) in the landscape, leaving traces of living or activity in the attractor (●). Plane B: Present archaeologist's movement in the landscape, revealing places of prehistoric attractors by positive test pit dig or surface registration (●). When no discovery, then no hits (●), while no hits by archaeologist, no projection of the prehistoric attractors (stray blue points). Plane C: Crossing point is recorded on the real landscape as a site (●). Picture is taken towards north, with modern shieling and cottages in Vabuleino, between the lake shoreline and the steep downhill in the backgound, northeastern bay of Lake Vavatn, Hemsedal, Buskerud County. Photographed in 1960 by Ola Rudvin. ©Hemsedal Bygdearkiv.

intervals, the probably medieval animal fall pits at a later time, and today the modern shieling, cottages and archaeological surveying creates more points in the Poincaré set. Further studies can focus on different scale levels and include material with different degree of provenience to get a more holistic understanding of past societies in the Norwegian high mountains.

References

Bang-Andersen, S 2000 Fortidens svarte gull – nærmere om datering og miljøtolkning av Fløyrliboplassene. *Frá Haug ok Heiðni*, 4/2000: 27–32.

Binford, L 1987 Searching for camps and missing the evidence. In: Soffer, O (ed.) *The Pleistocene Old World. Regional Perspectives.* New York and London: Plenum, pp. 17–31.

Boaz, J 1998 *Hunter-Gatherer Site Variability: Changing patterns of site utilization in the interior of eastern Norway, between 8000 and 2500 B.P.* Universitetets

Oldsaksamlings Skrifter. Ny rekke nr. 20. Oslo: Universitetets Oldsaksamling.

Cattani, M, Caldas, I L, de Souza, S L and Iarosz, K C 2017 Deterministic Chaos Theory: Basic Concepts. *Revista Brasileira de Ensino de Fisica*, 39(1), e1309. DOI: 10.1590/1806-9126-RBEF-2016-0185

Conneler, C. 2006 The Space and time of the châine opératoire: Technological approaches to past landscapes. *Archaeological Review from Cambridge*, 21(1): 38–44.

Faarlund, T and Aas, B 1991 Sør-Norges fjellskoger gjennom etteristiden. *Viking*, LIV-1991: 113–137.

Gleick, J 1987 *Chaos: Making a New Science*. New York: Viking Penguin.

Indrelid, S 1994 Fangstfolk og bønder i fjellet. Bidrag til Hardangerviddas førhistorie 8500-2500 år før nåtid. *Universitetets Oldsaksamlings Skrifter* Ny rekke nr. 17. Oslo: Universitetets Oldsaksamling.

Indrelid, S 2006 Vassdragsundersøkelser og tap av kildemateriale til vår eldste historie. In: Glørstad, H, Birgitte, S and Dagfinn, S (eds) *Historien i Forhistorien. Festskrift til Einar Østmo på 60-årsdagen.* Oslo: Kulturhistorisk museum, Universitetet i Oslo, pp. 21–28.

Ingold, T 1993 The temporality of the landscape. *World Archaeology*, 25(2): 152–174. DOI: 10.1080/00438243.1993.9980235

Jennbert, K 1984 *Den productiva gåvan. Tradition och innovation i Sydskandinavien för omkring 5 300 år siden.* Bonn: Rudolf Habelt Verlag. Serie: Acta Archaeologica Lundensia 4°. N° 16. Available at https://lup.lub.lu.se/search/publication/1536056 [Last accessed 10 March 2020].

Johansen, A B 1970 *Høyfjellsfunn ved Lærdalsvassdraget*. Oslo: Universitetsforlaget.

Johansen, A B 1978 *Høyfjellsfunn ved Lærdalsvassdraget II. Naturbruk og tradisjonssammenhenger i et sørnorsk villreinområde i steinalder*. Oslo: Universitetsforlaget.

Luhmann, N 1992 Hvorfor systemteori? In: Jacobsen, J C (ed.) *Autopoiesis. En introduktion til Niklas Luhmanns verden af systemer,* Vol. 1. København: Politisk Revy, pp. 10–20.

Madsen, T 1987 Where did all the Hunters go? An Assessment of An Epoch-Making Episode in Danish Prehistory. *Journal of Danish Archaeology*, 5: 229–239.

Madsen T 1988 Da jæger blev bonde. Om forklaring af kulturændringer i arkæologien. In: Madsen, T (ed.) *Bag Moesgårds maske. Kultur og samfund i fortid og nutid*. Aarhus: Aarhus Universitetsforlag, pp. 111–119.

Matsumoto, M and Uleberg, E 2002 Nye steinalderboplasser ved Vavatn i Hemsedal. In: Hofseth, E H (ed.) *UKM – En mangfoldig forskningsinstitusjon*. Oslo: Universitetets kulturhistoriske museer, Universitetet i Oslo, pp. 207–220. Series: Universitetets kulturhistoriske museer Skrifter nr. 1.

Matsumoto, M and Uleberg, E 2015 Digitizing archaeology in Norway. In: Piotrowska, K and Konieczny, P (eds.) *CONDITION.2015 Conservation and digitalization*. Gdańsk: National Maritime Museum in Gdańsk, pp. 159–164.

Meløe, J 1989 The Two Landscapes of Northern Norway. *Inquiry*, 31: 401–417.

Mikkelsen, E 1989 *Fra jeger til bonde. Utviklingen av jordbrukssamfunn i Telemark i steinalder og bronsealder.* Universitetets Oldsaksamlings Skrifter Ny rekke nr. 11. Oslo: Universitetets Oldsaksamling.

Moe, D, Indrelid, S and Kjos-Hanssen, O 1978 Environment and Early Man. *Norwegian Archaeological Review*, 11(2): 73–83.

Nyland, A J 2017a Quarrying in the Stone Age and Bronze Age in southern Norway studied as a socially situated phenomenon. *Bulgarian e-Journal of Archaeology*, 7: 133–154.

Nyland, A J 2017b Materialised taskscapes? Mesolithic lithic procurement in Southern Norway. In: Rajal, U and Mills, P (eds.) *Forms of Dwelling. 20 Years of Taskscapes in Archaeology*. Oxford and Philadelphia: Oxbow books, pp. 125–150.

Ore, C-E S 1998 Hvordan lage fagdatabaser for humanistiske fag. In: Aukrust, K H and Hodne, B (eds.) *Fra skuff til skjerm. Om universitetenes databaser for språk og kultur.* Oslo: Universitetsforlaget.

Persson, P 2017 The Earliest Settlement in the Middle Scandinavian Inland: A Discussion about Joel Boaz's Pioneers in the Mesolithic. In: Persson, P, Riede, F, Skar, B, Breivik, H M and Jonsson, L (eds.) *The Ecology of Early Settlement in Northern Europe. Conditions for Subsistence and Survival.* Sheffield, UK: Equinox Publishing, pp. 197–219. Series: The Early Settlement of Northern Europe, Volume 1.

Prescott, C 1995 *From Stone Age to Iron Age. A study from Sogn, western Norway*. Oxford: Tempus reparatum. Series: BAR International Series 603.

Schaller-Åhrberg, E 1990 Refittings as a method to separate mixed sites: a test with unexpected results.

Cziesla, E, Einckhoff, S, Arts, N and Winther, D (eds.) *The Big Puzzle. International Symposium on Refitting Stone Artefacts.* Bonn: Holos-Verlag, pp. 611–622. Series: Studies in Modern Archaeology, Vol. 1.

Selsing, L 2010 *Mennesker og natur i fjellet i Sør-Norge etter siste istid med hovedvekt på mesolitikum*. Stavanger: Arkeologisk museum, Universitetet i Stavanger. Series: AmS Varia 51. Available at http://hdl.handle.net/11250/181470

Sharp, L 1952 *Steel Axes for Stone-Age Australians. Human Organization*, 11(2): 17–22. Available at: https://www.jstor.org/stable/pdf/44123992.pdf

Stewart, I 2002 *Does God Play Dice? The New Mathematics of Chaos*. 2nd edition. Malden, Mass, USA: Blackwell.

Spencer-Wood, S M 2013 Nonlinear Systems Theory, Feminism, and Postprocessualism. *Journal of Archaeology*, Vol. 2013, Article ID 540912, 15 pages. DOI: 10.1155/2013/540912

Uleberg, E 2002 *Fra punkt til område. Steinbrukende tid i fjellet.* Unpublished Magister thesis, University of Oslo.

Uleberg, E 2003 Settlement patterns and landscape perception in Norwegian high mountains in the Stone Age. In: Tsonev, Ts and Montagnari Kokelj, E (eds.) *The Humanized Mineral World: Towards social and symbolic evaluation of prehistoric technologies in South Eastern Europe.* Proceedings of the ESF workshop, Sofia 3-6 September 2003. Liège–Sofia: Études et Recherches Archéologiques de l'Université de Liège, pp. 83–87. Series: ERAUL 103.

Uleberg, E 2004 Strange attractors in the high mountains. In: Fischer Ausserer, K, Börner, W, Goriany, M, and Karlhuber-Vöckl, L (eds) *[Enter the Past] The E-way into the Four Dimensions of Cultural Heritage. CAA 2003 Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 31st Conference, Vienna, Austria, April 2003.* Oxford: Archaeopress, pp. 444–447. Series: BAR International Series 1227.

Welinder, S 1988 The landscape of prehistoric man. *Memoranda Soc. Fauna Flora Fennica*, 64: 50–56.

Welinder, S 1989 Kaos i huvet på .... *META*, 4/1989: 51–52.

Welinder, S 1991 Drömmen om en arkeologisk vetenskap. *TOR*, 23/1990-1991: 235–257.

Wienberg, J 1989a Kaos i tiden. *META*, 3/1989: 63–70.

Wienberg, J 1989b Kaos i kaosforskningen. *META*, 4/1989: 53.

Communicating Archaeology

Carla Ardis et al.
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Un-#VEiLing the Potential of Social Media: Open Archaeology for Public Engagement

Carla Ardis
MOLA (Museum of London Archaeology). Northampton
carla.ardis@alumni.imtlucca.it

Riccardo Giovanelli
Ca' Foscari
University of Venice
riccardo.giovanelli@unive.it

Anna Bernardoni
Ca' Foscari
University of Venice
anna_ber@libero.it

Arianna Traviglia
Istituto Italiano di Tecnologia - Center for Cultural Heritage Technology
arianna.traviglia@iit.it

Abstract

Visualising Engineered Landscape (VEiL) is a landscape archaeology project based in Aquileia (Italy), which combines traditional methodologies with innovative digital technologies. Despite growing interest worldwide in Public Archaeology, in Italy *VEiL* is a unique example of an archaeological field survey project developing digital public engagement through Social Media (SM).

VEiL adopts a planned communication strategy, combining different SM (Twitter, Instagram, Facebook): multiple SM accounts enable customisation of contents according to the SM specific community, and to adapt communication patterns on the basis of audience response, matching public understanding and scientific authenticity. The adopted approach proved successful in reaching a broad and heterogeneous audience: the analytics show steadily increasing numbers of followers, ranging from academics to cultural associations, other public archaeology projects and general public.

Through digital engagement media, *VEiL* enables non-specialists to look behind the scenes of a research project. Posts that highlight diachronic landscape transformations are the ones with the highest interaction, suggesting a growing interest in local communities for local history: consequently, local landowners and residents feel more confident in sharing useful information with archaeologists. Direct, un-mediated interaction with *VEiL* project members increased followers also among scholars, attracted by the possibility of sharing reciprocal expertise in an informal fashion.

This paper describes the SM strategy, adopted by *VEiL*, of sharing the progress and results of ongoing research and how it fosters a direct connection between academics and public.

Keywords: Social media, Public Archaeology, public engagement, audience development, cultural heritage, field survey

Introduction

Social media (SM) is by now one of the most effective -if not the most effective- digital tools available in Public Archaeology, surpassing traditional websites and blogs in reaching out to both professional and general public audience interested in our past and in the research around it. With the world by now well into a social media revolution, it is no surprise that social media like Facebook, Twitter, Instagram -to cite a few- are used extensively for communication in archaeology.

Social Media refers to the use of web-based and mobile technologies to turn communication into an interactive dialogue: the term indicates a variety of internet-based applications including social blogs, microblogging, Internet fora, weblogs, podcasts, photo sharing, services review, social bookmarking, and more. For the purpose of this study we will use SM to indicate mainly services like microblogs (e.g.

Twitter), social networking sites (e.g. Facebook) and photo sharing (Instagram). These have emerged as leading instruments in the communication of Antiquity research (Walker 2014b) for their capacity of reaching out to a diverse and transversal public and are the force driving the advancement of the Digital Public Archaeology discipline.

Public Archaeology and Social Media. An Overview

In the last 20 years, the passage from the static Web 1.0 to the interactive Web 2.0 (or social Web) has opened countless possibilities in the field of communication, public outreach and interaction according to a *many-to-many* communication scheme. The appearance and development of Social Media, more specifically, has made available low-budget, flexible, interactive platforms that, despite privately owned and controlled, could be nevertheless considered 'democratic' since they enable users to reach a diverse and global public through the creation of 'decentralised communication channels' (Amedie 2005).

The archaeological community has been able to quickly recognise the potential of SM in terms of public engagement and visibility, and in the course of the last decades - especially after 2010 - the majority of archaeological museums, parks, organisations, private companies, research projects etc. have embraced the use of SM for communication and data dissemination. Social Media have thus become the bridgehead of Digital Public Archaeology. Stemming from traditional Public Archaeology, this is now a discipline - and a practice - debating issues related to the use of 'New Media' (in particular Web, SM platforms, mobile technologies) for engaging public on themes related to archaeology, developing methods and tools for public outreach and investigating new channels of online communication (Richardson 2013; Rocks-Macqueen 2016).

The debate surrounding Digital Public Archaeology has more recently shifted to considering specific challenges, such as the need of developing strategies for fast dissemination of new discoveries with the goal of enhancing the impact of archaeological research, gaining public support and ensuring effective research outcomes' communications in return of public funding (Bonacchi 2012; Richardson 2013). Influenced by post-processualism instances (Hodder 1999; Richardson 2013), the debate has focused also on novel means of interaction with a broad public through crowdsourcing (Bonacchi et al. 2015; Griffiths et al. 2015) and collaboratory/contributory digital practices able to create a new paradigm in the archaeological interpretation process (Bollwerk 2015; Bonacchi & Petersson 2017). Ethic issues (e.g. authority, privacy, inequalities in the access to the Internet, online abuse) related to Digital Public Archaeology have also been debated (Walker 2014a; Richardson 2018).

Nowadays, not only organisations and institutions with a 'physical' location and connected infrastructures - like museums and research centres-, but also 'virtual loci' - like archaeological projects and initiatives - make large use of SM, the majority of them showing a preference for micro-blogging applications (Twitter), visual storytelling tools (Instagram) and, most of all, platforms for social interaction (Facebook). The ways in which SM are exploited within archaeological projects and the level of awareness in topics related to Digital Public Archaeology is, on another hand, extremely diverse (Perry & Beale 2015). The absence of a clear SM strategy and the lack of a theoretical framework in which archaeological SM initiatives are developed affect often the use of SM within many projects, revealing an improvised (and often naive) approach to Digital Public Archaeology that disempower its potential.

While excavation or cataloguing projects are largely exploiting the power of digital applications for Public Archaeology (for example the projects Micropasts - Bonacchi et al. 2014-, *Portable Antiquities Scheme* - Bland 2009 -, *Open Salapia* - Baldassarre 2018 -, *The Vindolanda Trust* - Facebook2018a-, *MSU Campus Archaeology* - Brock & Goldstein 2015), landscape archaeology projects seem slower in grabbing the opportunities offered by SM to foster public engagement. Fieldwalking survey is certainly a methodology generally unknown to the broader audience, and, compared to traditional archaeological excavations, less visually impactful, if we consider that archaeological excavations' SM strategies are based on the publication of eye-catching images of unique monument discoveries, something that is unlikely in modern fieldwalking survey. However, field survey is also a discipline that enables many interactions with local inhabitants of a geographic area (farmers, landowners, administration authorities, or simple amateurs) and is well placed to highlight the history of the local heritage and its preservation within local communities than a single site; moreover, this applies to a broader geographic space. Actively incorporating digital Public Archaeology initiatives in field survey projects has therefore the potential of creating strong bonds with local communities that can support and facilitate the project itself.

In the following paragraphs, we are going to describe the experience developed within the survey project *VEiL - Visualising Engineered Landscape* with the goal of presenting and discussing our Social Media Strategy and the results so far achieved. *VEiL* represents in Italy a unique example of an archaeological field survey project widely exploiting SM potential to reach and engage a general audience.

In general, the use of SM in field survey activities suffers from the lack of published literature. Given these circumstances, any detailed comparative analysis and discussion on the broader theoretical framework within which our activity is set would have been impossible or only based on partial data.

The present work can be therefore considered as an attempt to start a conversation on SM approaches adopted within archaeological fieldwork projects, with the aim of understanding whether appropriate SM strategies could contribute in raising interest around field survey activities and how SM can be used to increase the international visibility of an archaeological area, to provide insights on the work of field archaeologists and on material culture, and to educate the public on challenges faced by cultural landscapes.

The VPAI - VEiL Project Public Archaeology Initiative

VEiL is an H2020 funded landscape archaeology project focused on investigating anciently engineered landscapes around Roman Aquileia (Italy) (Traviglia 2018). In order to improve public accessibility to the outcomes of the project, *VEiL* started *V_PAI (VEiL Project Public Archaeology Initiative)*, a project's stream that encompasses a variety of activities, all addressed to exploit SM power to reach a broad and diverse audience, including both specialists and general public. *VEiL* represents a distinctive instance within the above described framework of digital Public Archaeology in that it is applying SM public engagement strategies to a project that mainly entails field survey activities.

V_PAI is using a combination of multiple SM flanking a more traditional website: its SM space is defined by a Twitter account (Twitter 2018) since 28th October 2016, an Instagram profile (Instagram 2018) since 30th May 2017, a Facebook page (Facebook 2018b) since 17th October 2017, and a YouTube channel (YouTube 2018) since 16th May 2018.

Evolution of *V_PAI* strategy: the Interdependence with Public Responses

Since the beginning of our composite SM strategy, we needed to tackle some issues related to language and communication style. *VEiL* is an Italy based project but, having been initially funded by the European Community, had to reach an international audience. This circumstance, together with later confirmations from analytics (see 4.1), suggested for the use of English language, which, however, would have excluded wide portions of the Italian public, unfamiliar with it. The choice was to use both languages based on the particular SM's own characteristics. On Facebook, the same content is posted in both languages (Italian and English): Facebook is not bounded by characters limitation and it allows to select a preferred language for each post, offering the possibility to translate the contents; users can thus select whether to read the text in Italian or in English. The preferred language in which the post appears is the one selected by each user and/or it depends from the location of its IP address. On Twitter, due to characters limitations, posts are published only in English. On Instagram, text is extremely short, and communication is conveyed mainly by images and hashtags, reflecting the visual nature of this social platform.

The second challenge was the definition of a content strategy that had to reflect the main goal of V_PAI of reaching out for both general audience and archaeological community. Our posts aim to find a balance between public understanding and scientific authenticity: on one side, content must be appealing to the general public and understandable, without technicalities; on the other, posts must have an interest also for the scientific audience. Therefore, the approach adopted is to privilege scientific content and to convey it in a non-specialist, but still accurate language. Specialised language is not avoided, but technical details are always explained; objects and habits of the ancient world are frequently compared with contemporary tools and customs, in order to enable even non-specialised users to perceive them as something familiar. SM content is also determined by the 'intrinsic nature' of each platform, and the functionalities offered by it: Facebook allows to share detailed back-stories and long posts; Twitter, due to its "microblog" nature (Akcora & Demirbas 2010, Richardson 2012), enables to 'tweet' short status updates to a web-based public timeline; Instagram uses visually attractive content, with images being "a communicative act as a part of the whole social networking experience" (Akkanat 2012), and networking hashtags.

VEiL's SM strategy has changed through time: our communication patterns have become increasingly more structured, adapting to audience's responses. For the purpose of this papers, we have subdivided chronologically the trajectory of our SM strategy in 7 phases, reflecting the changes in our communication patterns. This temporal subdivision was deemed necessary in order to compare the results reached during each phase and to connect the variation in followers number and in public interaction to the strategic choices made in each phase.[1] The 5th phase, corresponding to the period when we switched to a more structured strategy, is subdivided in 9 subphases - reflecting the taking place of special events - in order to analyse both the characteristics of each event and their effects on the public engagement growth.

Phase 1: Opening. During this phase, in which only the Twitter account was active, we used our account in an experimental way, without following any structured strategy. Very few tweets were published during the first months. Content was rarely original: the account frequently shared news and tweets created by other Twitter users relevant to the project's purposes and interests, with the aim of creating a network including other archaeological research projects. During this period we aimed to build a followers consensus, mainly following other colleagues and archaeology-related accounts.

Phase 2: Fieldwork diary. For two weeks, between May and June 2017, the first *VEiL* fieldwork campaign since the launch of our SM took place: this occurrence provided the occasion to improve our SM communication on multiple levels: the Instagram account was opened and ad hoc content was daily posted on both platforms to share archaeologists' activities in the field. This new approach started to draw attention on *VEiL* accounts: other projects and institutions showed interests on what we were doing and dedicated some space to our research on their accounts.

Phase 3: Team management. Immediately after fieldwork, *VEiL* SM presence remained for a while scarcely planned. Twitter and Instagram accounts were managed simultaneously by different team members with no coordination, and posts essentially described moments of their archaeological activities within the project and other themes related to *VEiL*'s interests. The main goal during this period was to ensure public loyalty and to avoid a drop in the number of followers

Phase 4: Pre-fieldwork and fieldwork. A turning point in the development of *VEiL* SM strategy was the fieldwork season in November 2017, when, looking at the analytics referring to the previous period, we realised the need of a more structured communication and we started defining and implementing our strategy. We thus increased our SM presence by opening a Facebook page; secondly, two weeks before the survey campaign, we started posting every day content related to the designing and planning of a landscape archaeology project, from the analysis of remote sensing images, through the study of recovered artefacts, to the dissemination of the research results.

During fieldwork activities, we published daily multiple posts, but according to a more structured and planned strategy; with growing awareness of each platform mechanism, we started also to systematically collect information and to study public reactions to each post, in order to identify the themes preferred on each SM and/or by different public and to recognise the most engaging content.

Phase 5: Weekly schedule structured strategy. Further analytics inspection lead to acknowledge that posting all the year round (and not only during

1 Due to the offset in the accounts opening, only Twitter has 7 phases, while Instagram and Facebook has respectively 6 and 4.

fieldwork) was crucial to increase audience and to gain its loyalty. We thus started to design a well defined strategy, adapting the content to the social platform to be used. A specific role -both in the strategy conception and implementation- was assigned to each team member, in order to exploit each members' expertise and inclinations. Collected analytic data provided information for the identification of content that had generated an higher number of visualisations: during this period (about 7 months), *VEiL* social accounts started to post contents according to a regular weekly schedule, organised as three fixed appointments, each one devoted to a specific topic:

- **#MondayHistory**: dedicated to the history of the Roman city of Aquileia;
- **#WednesdayMethodology**: facing issues related to the methodology of archaeological research and enabling the public to see archaeologists at work;
- **#FridayFind** presenting each week an unusual find recovered during project fieldwork.

This weekly schedule was completed by other, more occasional, posts related to special occurrences, news or happenings; the routine was also occasionally disrupted during the participation to specific events (like conferences) by *VEiL* members: in this case the accounts published posts multiple times a day, sharing real time what was happening at the event. The hashtag **#VEiLinTransfer** was purposely created in order to gather all the content related to these events. To elucidate the impact that some of these activities determined on Twitter's followers growth, the phase 5 will be further divided in sub-phases. The planned weekly schedule (phase 5.1) was maintained over 2+ month in order to enable the public to get used to the new strategy and create strong public engagement. After this period, the scheduled posting plan was altered in connection with specific events. The first, in February 2018 (5.2), was a 4 days Public Archaeology Conference in Italy, TourismA 2018, described on *VEiL*'s SMs with the dedicated hashtag #passatofuturoTourismA18. Later, *VEiL* members participated to the "Computer Application and Quantitative Methods in Archaeology" conference held in Tubingen in March 2018, joining an international network through the hashtag #caatue (5.4). The third event that drew attention on *VEiL*'s SM was an only-twitter event, called #MuseumWeek, that took place at the end of April 2018, during which *VEiL*'s SMs used the official hashtag of the event to build links with other Italian institutions (5.6). The last event was the international conference YoCoCu 2018, held in Matera in May, that was used to forge connections with professionals through the twitter network **@yococu** (5.8). Between each event, *VEiL*'s SMs reverted back to the usual routine (5.3, 5.5, 5.7), maintaining growing followers acquisition rates as a backlash of the events, especially on Twitter.

Phase 6: Artefact study campaign. The next turning point in the development of *VEiL* SM strategy was the artefact study campaign that took place in Summer 2018. In that period, the regular weekly schedule was put on hold and SM accounts posted content daily, sharing in real time the research activities. Three posts were scheduled every day and their content included information on *VEiL* members, the study routine and the material culture being analysed. The growth in the number of followers reached in this short period demonstrated again how the 'real-time archaeological work' contents can increase engagement rates and the effectiveness of conveying unique content, both in boosting interest and in reaching new public.

Phase 7: new weekly structured strategy (current). A new strategy started to be implemented after the artefact study campaign and it was again organised following weekly fixed appointment, continuing up to now. The current weekly schedule is organised as such:

- **#VEiLers**: published on Tuesday, these posts present team members at work, detailing project methodology and introducing the real actors of this project. Replacing **#WednesdayMethodology**, these posts portray team member busy in different fieldwork tasks showing work routine;
- on Wednesday, with the header "in the meantime, in **#Aquileia**", *VEiL* social accounts circulate content related to archaeological projects or other initiatives that took place

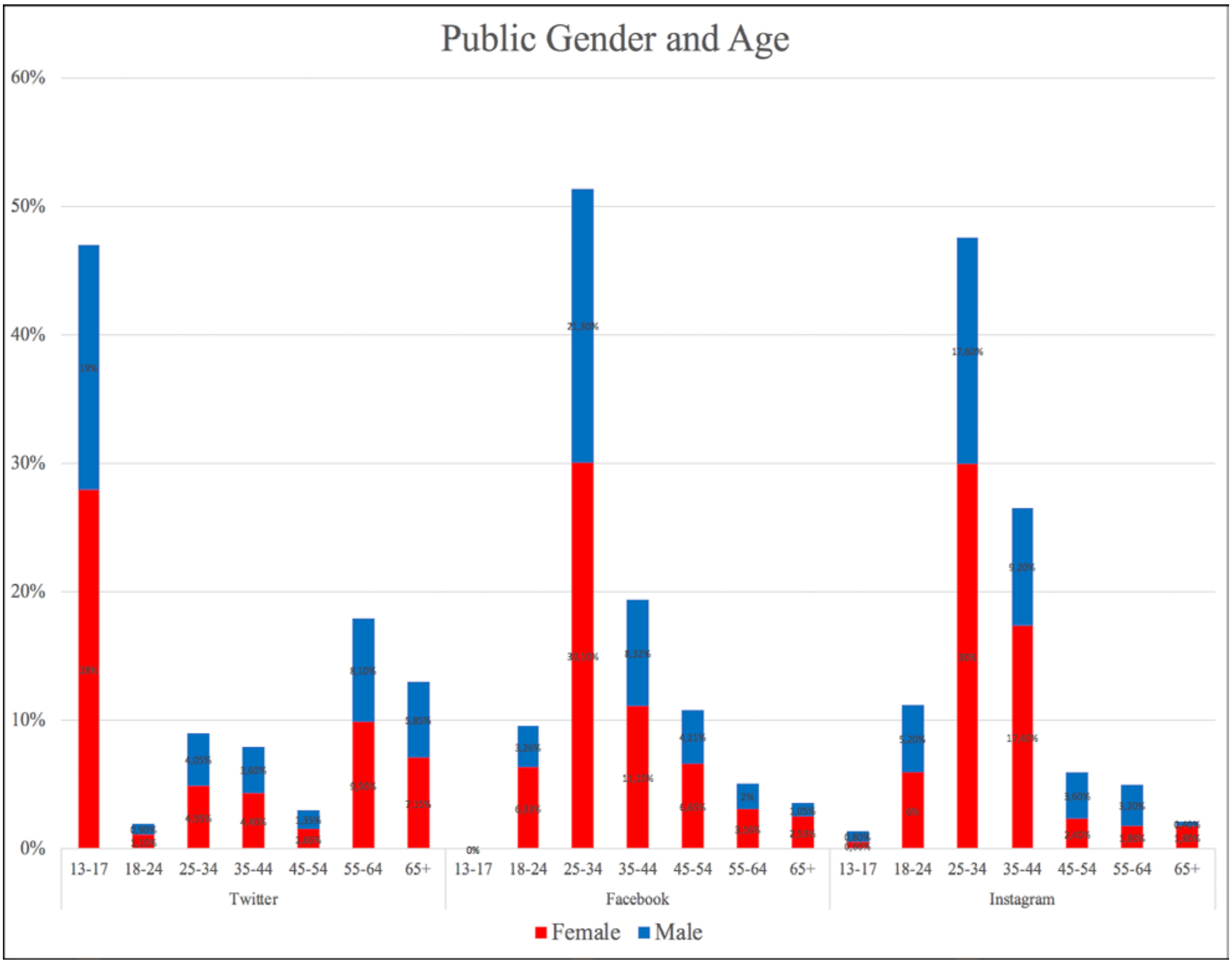

Figure 1. *VEiL* project's public gender and age.

in Aquileia: this kind of posts are intended to foster the creation of a network with local institutions and to promote an informal interaction among different stakeholders working in the same area;

- we maintained **#FridayFinds** in the new schedule, as analytics demonstrated that is the most effective and engaging content for public over the whole period of life of *VEiL* SM accounts. In order to increase public engagement and to foster public interaction, posts occasionally contain a direct call to action: through riddles or direct questions, followers are called to recognised the object portrayed in the posts. We also use **#FridayFinds** posts to gain suggestions from expert public in relation to artefacts, the nature of which is dubious: this weekly post is highly appreciated by material culture scholars, attracted by the possibility to share preliminary results without the waiting time of official publications and comparing finds from different sites in an informal way;

- during the weekend, **#DiscoveringAquileia** presents each week an archaeological area of the city with the goal of improving public knowledge of the city where the project takes place. The topic was chosen specifically for the summer period, when tourism in Aquileia is at its peak: these posts are addressed mainly to this segment of public, providing useful information for the visit to the city.

The new strategy is enriched by a new graphic design for the visual content, with a coloured label assigned to each image according to each theme (orange for **#VEiLers**, light-blue for **#FridayFinds**,

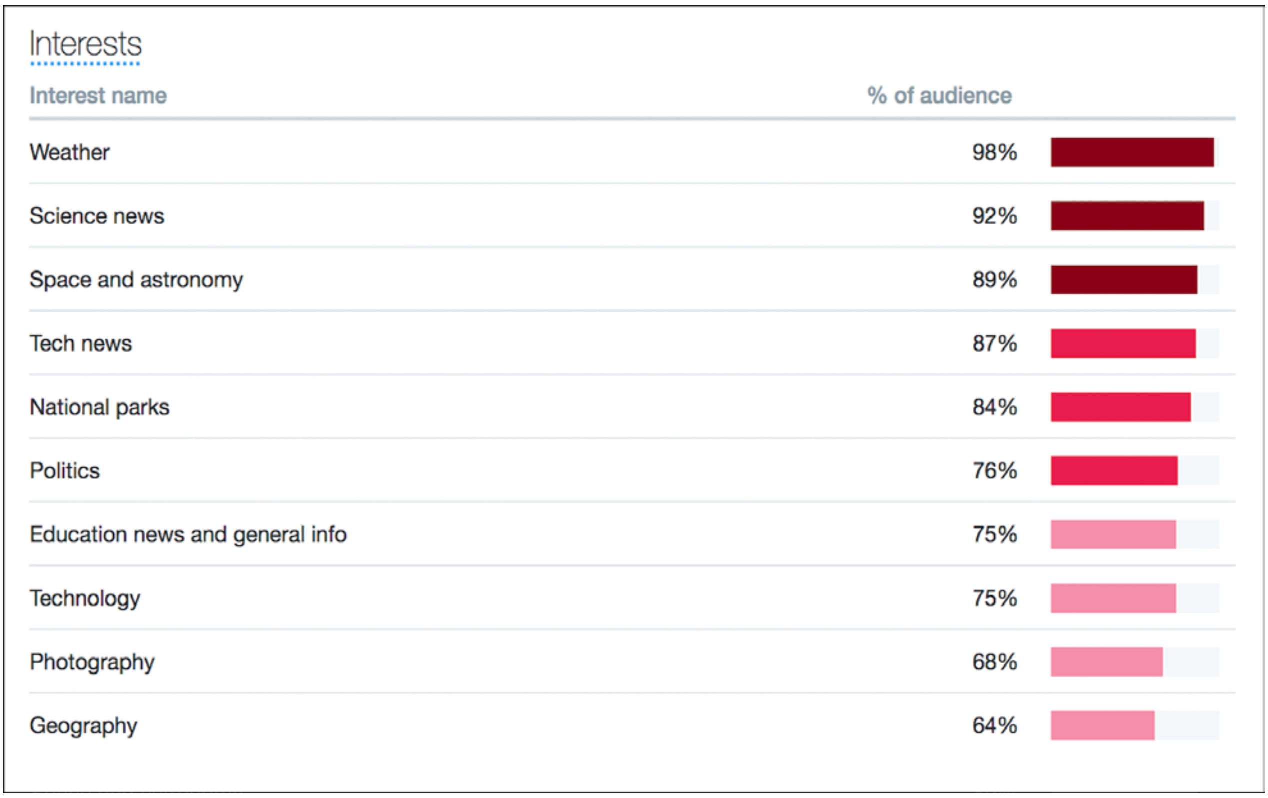

Figure 2. *VEiL* project's Twitter followers interests.

green for **#DiscoveringAquileia**) to easily recognise the topic of each post.

Results so far reached are going to be discussed in detail below.

Insights and Analytics

Analytics have been constantly monitored using tools provided by each SM platform to better understand the interests of the public and the volume of engagement each post and each strategy change have determined. Analytical data collection was made both automatically and manually in order to perform comparative analysis between the results. Key metrics selected for the study of our SM strategy and for understanding our public's inclinations are multiple: qualitative and quantitative metrics about gender, age and nationality, coupled with more subtle information provided by Twitter Analytics regarding the interests of the followers, were fundamental to understand the potential and the geographical coverage of each platform. Quantitative metrics related to the traffic volume provided by each account (i.e. visualisations, interactions, impressions, likes, clicks, retweets, sharing, comments, answers and followers growth) have been collected on a daily/post basis and turned into mean rates to compare strategies across time.

As analytics and insights are accessible only by the owners and managers of the SM profile and given the absence of published data relative to other similar projects, it is not possible to compare *VEiL*'s quantitative and qualitative parameters with other projects' ones. In absence of accessible structured data, analysing merely public parameters of other projects could have led to an incorrect interpretation. Followers' number could not be considered a way to measure a page/profile effectiveness in reaching the public, since all the SM platforms provide paid services to sponsor the page, to improve the visibility of the account themselves, and even to purchase followers. It must be noted that, throughout all the phases presented above, *VEiL* Social media did not make any use of sponsored content. Furthermore, analysing publicly visible interactions is not enough, because real interactions should take into account also the number of users who actually see the content, an information that Social Network platforms share only with the account owner(s). For this rea-

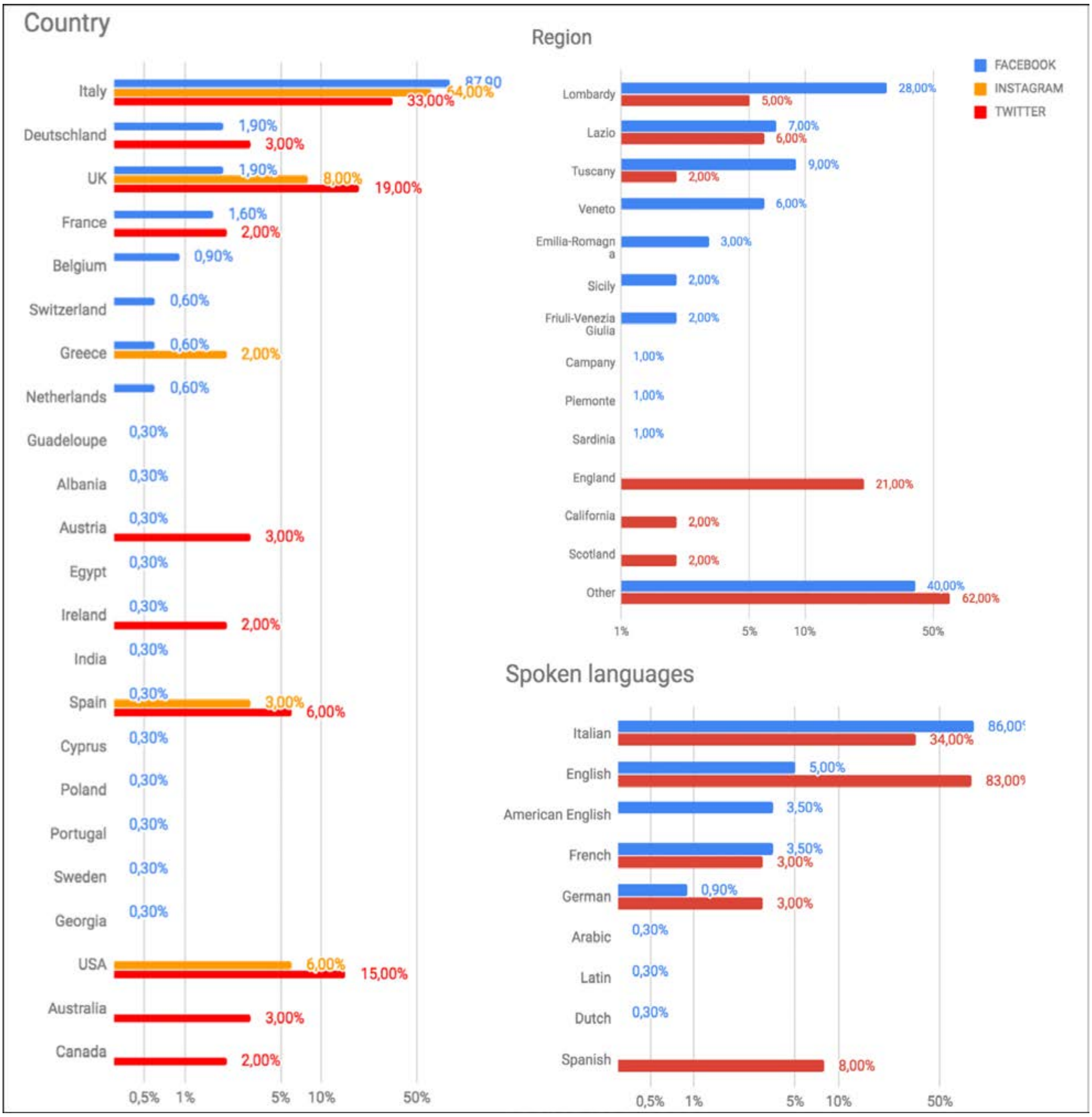

Figure 3. National, regional and linguistic origin of the public of *VEiL* project's SM platforms.

son, our analysis focuses only on *VEiL*'s results and achievements, with the hope that in the future other projects will start sharing their analytical data, providing means for a more detailed and comprehensive comparative analysis.

Public quantitative and qualitative metrics

The nature of each of the used SM platforms is reflected in the different type of followers. As data collected show, *VEiL* project's public is quite heterogeneous across the three used platforms; almost all ages and both genders are represented, with a slight predominance of female users (always around 60%). Nonetheless, there is a significant difference between Twitter public, on one side, and Facebook and Instagram public[2] on the other. Instagram and Facebook publics appear similar in terms of age, with around 50% of the followers in the 25-34 y.o. range and a noticeable presence

2 Data shown for Twitter Public are from the public until March 2018, for Instagram and Facebook until July 2018. Privacy rules set on Twitter after that date make impossible to observe the gender of the followers.

			Posts			Visualisations/Impressions			Interactions/saves			Link/profile clicks			Sharing		Likes			Answers/comments			New followers		
	Starting	Days	Twitter	Facebook	Instagram	Twitter	Facebook	Instagram	Twitter	Facebook	Instagram	Twitter	Facebook	Instagram	Twitter	Facebook	Twitter	Facebook	Instagram	Twitter	Facebook	Instagram	Twitter	Facebook	Insgagram
Phase 1	28/10/2016	213	10			636			213			3			1		3			0			6		
Phase 2	29/05/2017	15	30		54	5597			205		2	2			4		57		602	3		6	30		46
Phase 3	13/06/2017	110	41		14	26001			576		0	24			44		124		223	4		0	27		1
Phase 4	01/10/2017	61	58	57	26	63770	50226	2660	1411	1719	0	117	6	7	203	90	444	704	537	13	44	12	89	227	63
Subphase 5.1	01/12/2017	75	31	31	13	106606	22253	1777	2086	944	1	196	0	5	256	64	713	471	202	30	20	11	107	10	0
5.2 Toursima 2018	14/02/2018	4	11	4	1	7180	2616	171	240	100	0	8	1	2	22	6	77	50	18	2	1	0	20	0	0
Subphase 5.3	19/02/2018	26	15	14	8	45486	6299	1046	988	296	0	82	0	7	112	19	270	148	165	4	5	3	22	6	15
5.4 CAA 2018	17/03/2018	9	31	6	1	16184	2282	124	453	116	0	23	0	1	18	6	98	63	8	4	0	0	22	4	2
Subphase 5.5	26/03/2018	28	16	15	6	40447	6501	612	789	327	0	44	0	6	78	15	230	131	48	7	7	0	22	10	7
5.6 #MuseumWeek	23/04/2018	8	31	4	14	81551	729	1498	1137	49	0	49	0	4	534	2	1051	34	134	83	1	0	22	1	0
Subphase 5.7	01/05/2018	19	14	12	9	58597	6997	1607	1041	302	1	42	0	13	182	6	403	102	147	21	4	2	19	2	13
5.8 YOCOCU 2018	20/05/2018	8	16	8	2	16626	2271	248	367	139	0	14	0	0	67	5	137	83	27	9	3	0	19	34	0
Subphase 5.9	28/05/2018	33	16	16	9	64043	3248	1660	1289	228	0	40	0	11	149	3	379	86	144	49	0	3	25	5	14
Phase 6	30/06/2018	11	25	28	12	61684	9170	2334	1857	682	3	108	1	27	135	14	403	318	226	13	21	9	50	10	36
Phase 7	11/07/2018	27	19	21	3	72442	4574	595	1172	254	0	101	0	9	201	3	513	109	68	15	3	0	46	5	10
TOTAL		647	364	216	172	666850	117166	14332	13824	5156	7	853	8	92	2006	233	4902	2299	2549	257	109	46	526	314	207

Table I: *VEiL* project's Twitter, Facebook and Instagram resulting metrics, subdivided by each phase and sub-phase of the strategy.

for the age ranges 18-24 and 35-54, which reflects the fact that these platforms are used by a younger audience. Twitter public is quite different, with age range between 55-64 years and 65+ well represented, as well as an unusual presence (47%) of followers aged 13-17. This can be explained as a misrepresentation of data, linked to the fact that institutional accounts often declare as date of birth the date of institution founding (or project starting for projects) or leave it blank, letting Twitter automatically registers an age range from 13 to 55. Even excluding this range from the analysis, we can see that the Twitter public is older than the Instagram and Facebook ones, and requires therefore a customised communication.

Followers' interest analytics provided by Twitter (see figure 2) seem to show that our Twitter followers are part of an educated and knowledgeable public, which likely utilise it as a "news media" (Bennato, Benhotman & Pancones 2011; Java, Song, Finin et al 2007) rather than a "phatic media" (Miller 2008). The strong presence among our followers of archaeological institutions, museums, projects and professionals confirms this view.

Like Twitter, Instagram works well to create networks for information exchange among institutions and associations. This possibility is instead discounted on Facebook, since this platform does not allow direct interactions between pages, making it more difficult to foster networking among projects or organisations. Our Facebook followers are thus mainly private profiles. Unfortunately, more in-depth information about Facebook and Instagram public's interests are not available due to the different privacy rules of these platforms' analytics.

Public nationality and spoken language are other key metrics, that initially enabled us to determinate the style and the preferred language on each SM. There are slight differences across our three SM platforms. Italy is the predominant country of the public across all the platforms (Figure 3). On Facebook Italy is the only country significantly represented, while on Twitter there is a strong presence of a UK based public and a slight presence of Americans and Spanish; for Instagram we record a good presence of UK and USA followers. It's interesting to point out here that up to the **#MuseumWeek** (5.6), Twitter used to have an absolute predominance of UK followers, that now represent only the 19% of the followers. This can be explained with the high number of interactions with Italian institutions and personal profiles during that event, which resulted in a fast growth of Italian based public on this specific SM.

Twitter and Facebook insights provide also information about the regions of origin, although in an incomplete way. figure 3 shows the geographic spread of our public: on Facebook, the Italian administrative regions with highest numbers of followers are those in which *VEiL*'s members live and work, reflecting the role of personal connections. On Twitter, we see a different behaviour, with less depen-

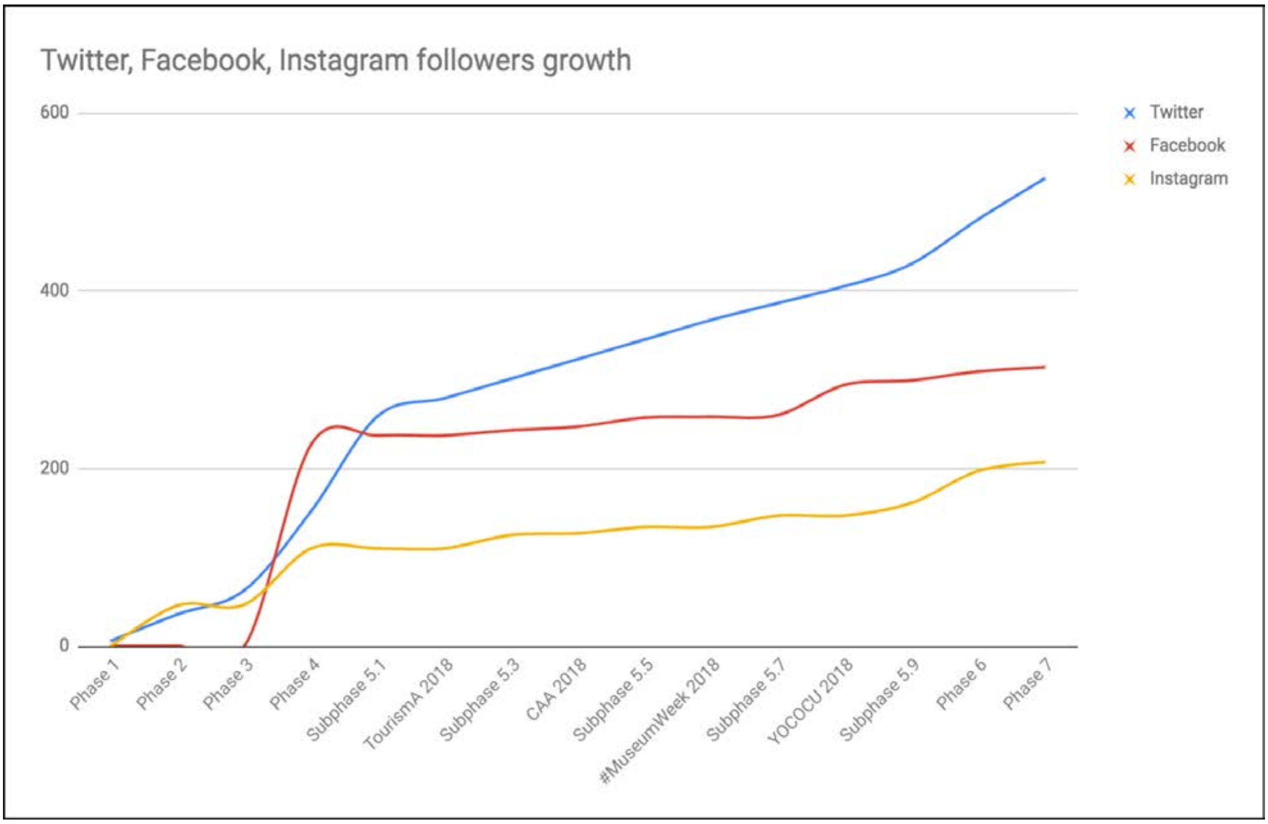

Figure 4. *VEiL* project's followers growth over time.

dency from the members personal connections and a wider reach.

Spoken languages plot of Facebook shows an almost absolute prevalence of Italian language followers; on Twitter, instead, we can appreciate a predominance of English speakers: this information was at the basis of the decision to write tweets in English.

As stated above, Facebook remains connected to the local communities and reaches less effectively an international and wider public, thus pointing out the higher potential of Twitter.

Engagement Quantitative Metrics

Metrics like numbers of consumptions (Heinonen 2011), interactions, and followers' gains have been collected on a daily basis since the beginning of the project. Data were then subdivided by each of the phases presented above, and interactions were calculated per each subphase. The resulting values are synthesized in table I. Phases and sub-phases had different lengths, ranging from 4 days to 213 days. Raw data like these provide a way to compare information relative to the same phase on three SM platforms and to evaluate the relationships between different key metrics. For example, the metrics of subphase 5.4 and subphase 5.6, which share a similar time span and the same number of tweets on Twitter, demonstrates that the number of answers -meaning the constant interaction with other users under each original post- is correlated to the overall engagement of followers with the posted content more than to the number of tweets.

Analytics also enable comparison and evaluation of the followers growth over time, as shown in figure 4: Instagram proved to be less successful in attracting followers while Twitter started to grow faster since the beginning of the PA initiative and never lost its positive trend. This, with the comparative observation of the values collected in table I, suggests that type of content shared by VPAI is more suitable for a microblogging platform and, in general, more attractive for Twitter users: the total number of visualisations so far obtained on Twitter overcome by almost the 600% those on Facebook and by almost the 6000% the ones on Instagram, which, instead, continues to grow at a slow pace.

	Period	Days	Tweets	Visualisations	Interactions	Clicks	Retweets	Likes	Answers	New Followers
Phase 1	28/10/2016	213	10	3,0	1,0	0,0	0,0	0,0	0,0	0,0
Phase 2	29/05/2017	15	30	373,1	13,7	0,1	0,3	3,8	0,2	2,0
Phase 3	13/06/2017	110	41	236,4	5,2	0,2	0,4	1,1	0,04	0,2
Phase 4	01/10/2017	61	58	1045,4	23,1	1,9	3,3	7,3	0,2	1,5
Subphase 5.1	01/12/2017	75	31	1421,4	27,8	2,6	3,4	9,5	0,4	1,4
Subphase 5.2 - TourismA event	14/02/2018	4	11	1795,0	60,0	2,0	5,5	19,3	0,5	5,0
Subphase 5.3	19/02/2018	26	15	1749,5	38,0	3,2	4,3	10,4	0,2	0,8
Subphase 5.4 - CAA 2018	17/03/2018	9	31	1798,2	50,3	2,6	2,0	10,9	0,4	2,4
Subphase 5.5	26/03/2018	28	16	1444,5	28,2	1,6	2,8	8,2	0,3	0,8
Subphase 5.6 - MuseumWeek	23/04/2018	8	31	10193,9	142,1	6,1	66,8	131,4	10,4	2,8
Subphase 5.7	01/05/2018	19	14	3084,1	54,8	2,2	9,6	21,2	1,1	1,0
Subphase 5.8 - YOCOCU 2018	20/05/2018	8	16	2078,3	45,9	1,8	8,4	17,1	1,1	2,4
Subphase 5.9	28/05/2018	33	16	1940,7	39,1	1,2	4,5	11,5	1,5	0,8
Phase 6	30/06/2018	11	25	5607,6	168,8	9,8	12,3	36,6	1,2	4,5
Phase 7	11/07/2018	27	19	2683,0	43,4	3,7	7,4	19,0	0,6	1,7

Table II: *VEiL* project's Twitter resulting daily mean values.

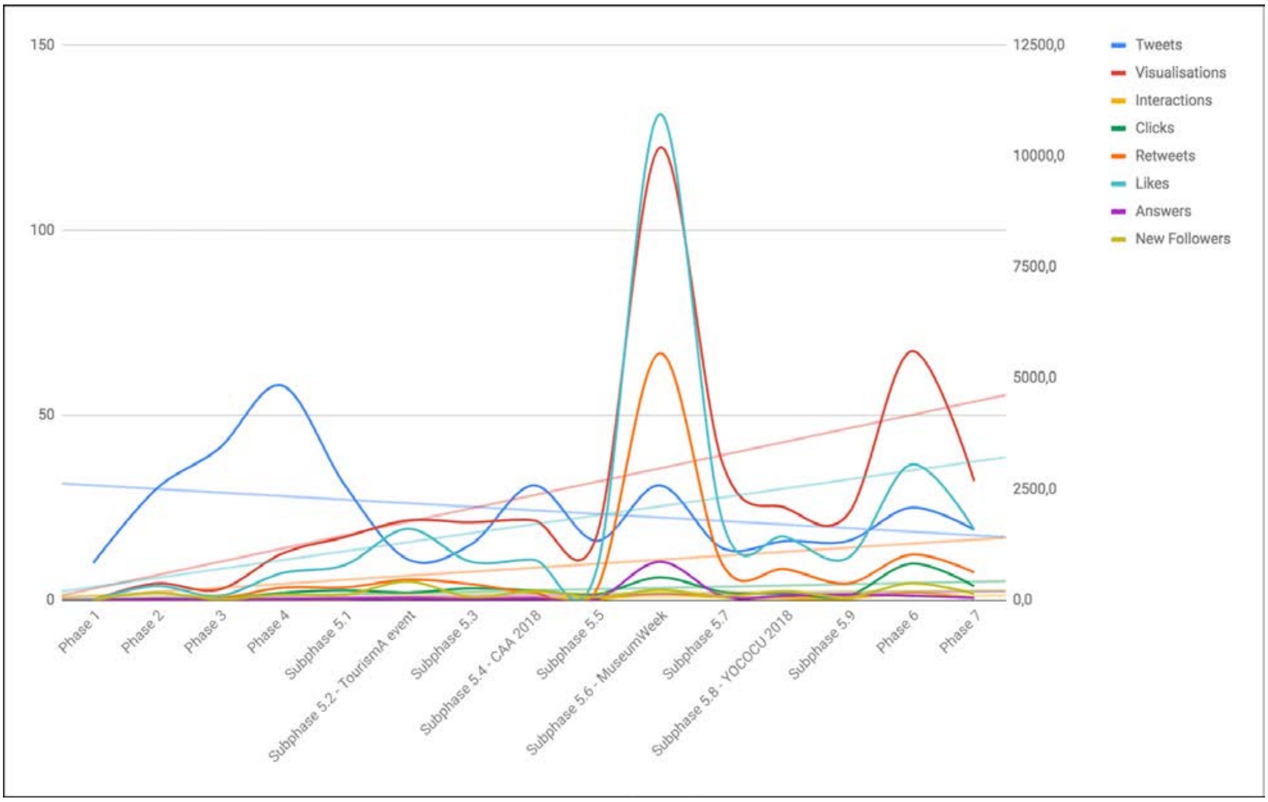

Figure 5. *VEiL* project's Twitter daily mean values plot with tendencies lines.

For further and more consistent analysis, the arithmetic mean of each value has been calculated on the basis of the length of each phase, in order to understand what influences the growth or decrease of the public engagement. The resulting daily values have been synthesised in tables II, III and IV and graphically rendered in figures 5, 6 and 7.

Twitter Analysis

Table II shows Twitter key metrics resulted from the means calculation over each phase. The first possible deduction is that Twitter saw a fast growth in phase 4, showing the interest of public for fieldwork activities undertaken in that peri-

	Period	Days	Tweets	Visualisations	Interactions	Clicks	Retweets	Likes	Answers	New Followers
Phase 1	28/10/2016	213	10	3,0	1,0	0,0	0,0	0,0	0,0	0,0
Phase 2	29/05/2017	15	30	373,1	13,7	0,1	0,3	3,8	0,2	2,0
Phase 3	13/06/2017	110	41	236,4	5,2	0,2	0,4	1,1	0,04	0,2
Phase 4	01/10/2017	61	58	1045,4	23,1	1,9	3,3	7,3	0,2	1,5
Subphase 5.1	01/12/2017	75	31	1421,4	27,8	2,6	3,4	9,5	0,4	1,4
Subphase 5.2 - TourismA event	14/02/2018	4	11	1795,0	60,0	2,0	5,5	19,3	0,5	5,0
Subphase 5.3	19/02/2018	26	15	1749,5	38,0	3,2	4,3	10,4	0,2	0,8
Subphase 5.4 - CAA 2018	17/03/2018	9	31	1798,2	50,3	2,6	2,0	10,9	0,4	2,4
Subphase 5.5	26/03/2018	28	16	1444,5	28,2	1,6	2,8	8,2	0,3	0,8
Subphase 5.6 - MuseumWeek	23/04/2018	8	31	10193,9	142,1	6,1	66,8	131,4	10,4	2,8
Subphase 5.7	01/05/2018	19	14	3084,1	54,8	2,2	9,6	21,2	1,1	1,0
Subphase 5.8 - YOCOCU 2018	20/05/2018	8	16	2078,3	45,9	1,8	8,4	17,1	1,1	2,4
Subphase 5.9	28/05/2018	33	16	1940,7	39,1	1,2	4,5	11,5	1,5	0,8
Phase 6	30/06/2018	11	25	5607,6	168,8	9,8	12,3	36,6	1,2	4,5
Phase 7	11/07/2018	27	19	2683,0	43,4	3,7	7,4	19,0	0,6	1,7

Table III: *VEiL* project's Facebook resulting daily mean values.

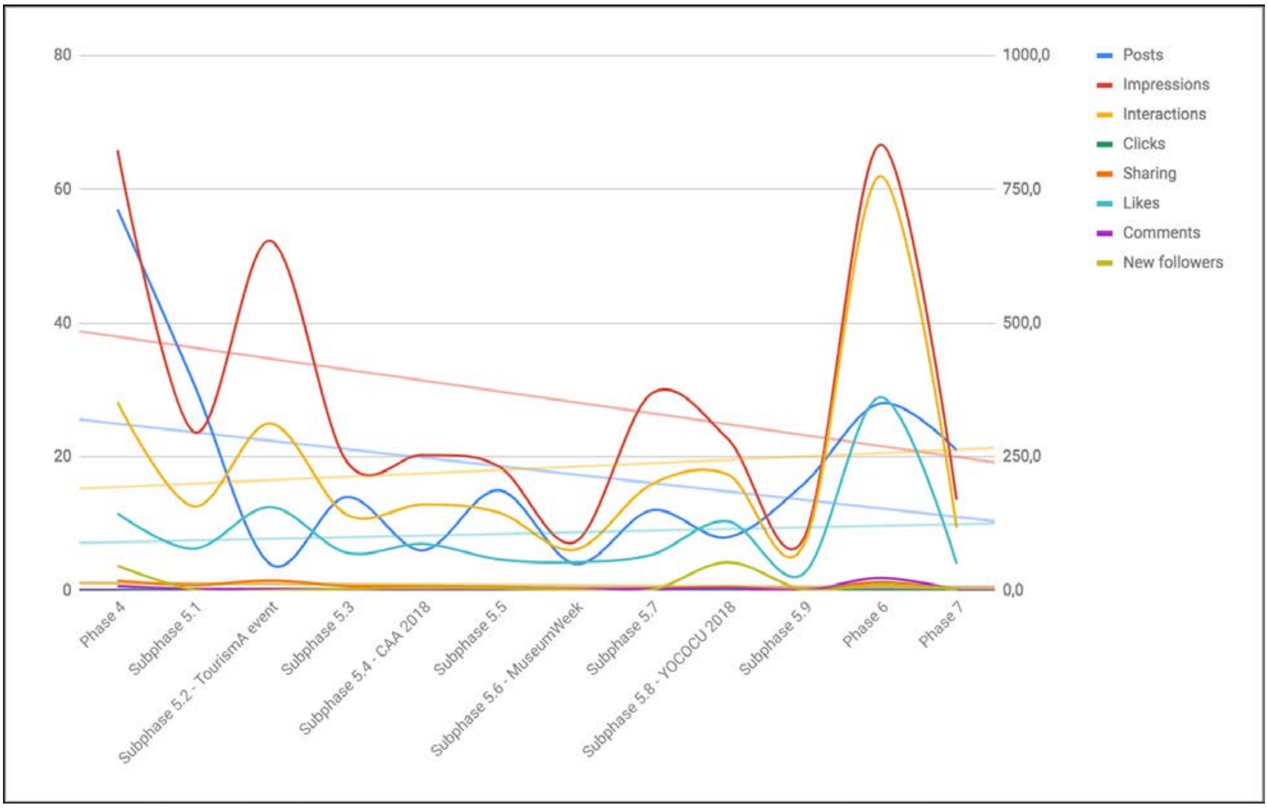

Figure 6. *VEiL* project's Facebook daily mean values plot with tendencies lines.

od. From this moment, the growth of the account seems constant in all the metrics observed, with some standard error and one exception, clearly seen in subphase 5.6 during the #MuseumWeek. This event reached exceptional results, gaining almost six times more visualisations, interactions and clicks compared to the previous phases and subphases, and almost twenty times more retweets and likes: the account never saw a similar engagement rate before and never experienced similar long lasting effects; indeed, the three subphases after the **#MuseumWeek** registered a decreasing trend, but compared to the results collected during the phases before that event, they saw numbers

	Period	Days	Posts	Impressions	Saves	Profile views	Likes	Comments	New followers
Phase 1									
Phase 2	29/05/2017	15	54		0,1		40,1	0,4	3,1
Phase 3	13/06/2017	110	14		0,0		2,0	0,0	0,0
Phase 4	01/10/2017	61	26	43,6	0,0	0,1	8,8	0,2	1,0
Subphase 5.1	01/12/2017	75	13	23,7	0,0	0,1	2,7	0,1	0,0
Subphase 5.2 - TourismA event	14/02/2018	4	1	42,8	0,0	0,5	4,5	0,0	0,0
Subphase 5.3	19/02/2018	26	8	40,2	0,0	0,3	6,3	0,1	0,6
Subphase 5.4 - CAA 2018	17/03/2018	9	1	13,8	0,0	0,1	0,9	0,0	0,2
Subphase 5.5	26/03/2018	28	6	21,9	0,0	0,2	1,7	0,0	0,3
Subphase 5.6 - MuseumWeek	23/04/2018	8	14	187,3	0,0	0,5	16,8	0,0	0,0
Subphase 5.7	01/05/2018	19	9	84,6	0,1	0,7	7,7	0,1	0,7
Subphase 5.8 - YOCOCU 2018	20/05/2018	8	2	31,0	0,0	0,0	3,4	0,0	0,0
Subphase 5.9	28/05/2018	33	9	50,3	0,0	0,3	4,4	0,1	0,4
Phase 6	30/06/2018	11	12	212,2	0,3	2,5	20,5	0,8	3,3
Phase 7	11/07/2018	27	3	22,0	0,0	0,3	2,5	0,0	0,4

Table IV: *VEiL* project's Instagram resulting daily mean values.

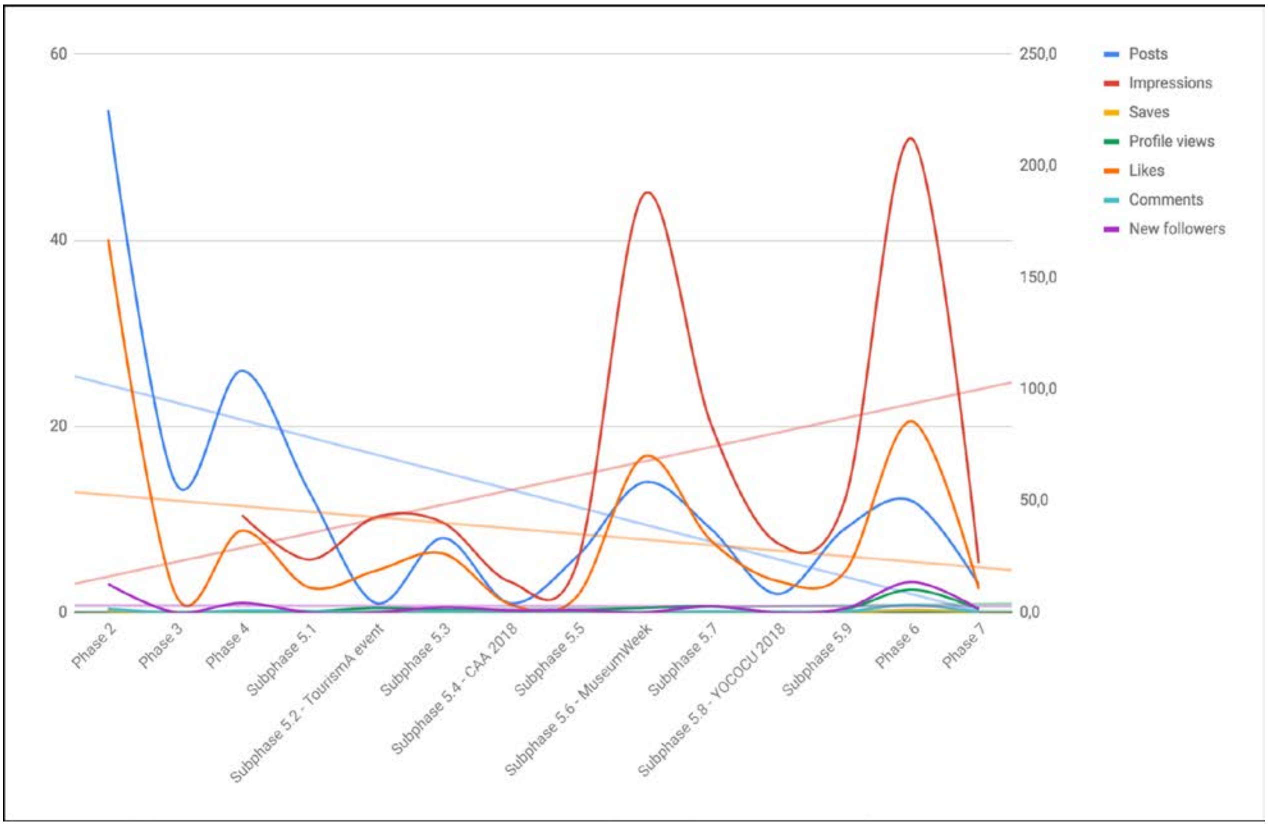

Figure 7. *VEiL* project's Instagram daily mean values plot with tendencies *lines.*

still significantly higher and rate never fell under the previous values.

Table II shows another characteristic common of all the four events, i.e. the attainment of a higher number of new followers as a consequence of an 'event' compared to any other phase, with the exception of the recent phase 6. This fact confirms once again the importance of the networking on Twitter on occasion of special events of reciprocal interest in order to create a core group of long lasting and interacting followers.

Phase 6 represents another turning point: here, after the immovability seen in Subphase 5.9, analytics show a new fast growth, due to the artefact study campaign: the new strategy adopted after that event together with the long-lasting effects of the previous fieldwork, is showing engagement rates comparable only with the subphase 5.7. Tendencies lines presented in figure 5 are indeed positive and show a growing trend for all the engagement key metrics selected, demonstrating the efficacy of the strategies adopted so far.

Facebook Analysis

Table III collects Facebook key metrics resulted from the means calculation over each phase. The account opened during the first fieldwork activities. A comparison with Twitter's metrics shows that during this phase Facebook appears to have gained better results, followed by a steadfast decline during the next phase. This may be explained by the nature of the 'core public' in this platform: this is built mainly from personal "contacts" of *VEiL* team members, people not necessarily interested in the archaeological discourse, explaining the key metrics volatility over time.

Analysis of the subphases related to events shows how this platform performed differently compared to Twitter: **#MuseumWeek**, being a virtual event, did not concur to stir interest and obtain new followers, while the conferences TourismA 2018 and YoCoCu2018 determined peaks in new followers rate.

Phase 6 represents also here a defining moment: the real-time description of the work routine of *VEiL*'s team and insights on their research profiles determined an increase of impressions, interactions, likes and comments, never seen so frequent before. Tendencies lines (figure 6) show that while impressions have a negative tendency, likes and interactions rate, together with followers (figure 4) are still growing. The new strategy, more focused on team members' daily work, has a good chance to boost the followers of *VEiL*'s Facebook page.

Instagram Analysis

Instagram key metrics mean rates have been collected in table IV. It was not possible to collect data from impressions, profile views and comments prior the Facebook page opening due to internal limitations. Due to the fact that there is not an internal tool for metrics extraction in Instagram, data have been collected manually from each post: for this reason, it is necessary to keep in mind that Instagram data here analysed represents posts engagement and not the whole profile or page engagement as seen for Facebook and Twitter. However, due to the nature of this specific SM, single-post oriented, it can be assumed that there wouldn't be significant differences.

Of the SM adopted within V_PAI Instagram appears indeed to be providing the worst results. Both raw data in table I and mean rates in table IV portray a remarkably lower public engagement than Twitter and Facebook. This can be explained by the nature of this SM based on visually attractive posts without textual content. Indeed, fieldwork activities, with their highly appealing visual content, enabled to attain followers' rates superior to 1.0, while during the structured strategy period of Phase 5 they have been equal to 0. Likes and impressions rates demonstrate the same behaviour, except for the #MuseumWeek sub-phase (5.6), which gained slightly better results Tendencies lines displayed in figure 4 are the less promising among the three SM, but the impressions rates plot is now showing a positive trend; interactions with other projects together with a more targeted use of combined broad and specific hashtags and the adoption of the new strategy will likely provide positive results in a short time frame.

Conclusion

Experience has demonstrated how managing effectively our SM for communicating research requires vision, accurate planning, and systematicity, and even developing digital communication skills that, as archaeology practitioners, we initially had to cultivate through self- training before being able to master. SM offer us analytic tools that provide direction and support our efforts of expanding the number of people we are communicating with: the analyses that we now methodically undertake on SM mined data enable us to understand better both our work and our public's requests and provide insights that can help us to shape new strategies to increase our audience. In just one year the three SM platforms of our project went from 82 to 1,047 total followers, from 209 to 2,542 total interactions per month and from just 8,000 to 123,169 total consumptions per month, reaching in the whole SM lifetime - for a total of 752 posts - 32,541 total interactions and the remarkable number of 798,000+ total consumptions.

The positive trends in the growth of our audience that we are witnessing through evaluation of the SM metrics demonstrate how a correct SM strategy can create the conditions for gaining the interest of a large transversal public with a broad geographic distribution. Thus, if from one side we are using SM to bridge academic research with general public, from the other the relations that our SM enable to establish with research teams at other universities or research centers are fostering cooperation among cultural heritage experts.

Last but not least, the SM initiative is promoting the involvement of the local resident community in our fieldwork research activities: the possibility provided by SM to directly interact with the archaeologists (through a digital medium) prompts locals to share crucial information deriving from their profound knowledge of the configuration of the landscape they live in.

Based on our direct experience, it's self-evident that SM have the potential to fundamentally change the character of our social and professional interactions, both on an interpersonal and a community level, and even the way we can collect data to be reused (following appropriate validation) within our research. Regrettably, digital public archaeology scholarship is not yet fully informed by established theory and methods that can support this journey, with the discipline just in its infancy, progressing through a handful of dedicated practitioners. Nevertheless, current trends in both research and practice of Digital Public Archaeology, as well as the role that research communication is increasingly being assigned by funding organisations (for example, the European Commission), leave few doubts that in the next years more human and financial resource investments will be necessary to promote the discipline and thus ensure an informed and knowledgeable cultural heritage communication.

References

Akcora G C, Demirbas M 2010 *Twitter: Roots, Influence, Applications. Technical Report*, Department of Computing Science and Engineering State University of New York at Buffalo. Available at: ftp://coggsworth.cse.buffalo.edu/pub/tech-reports/2010-03.pdf [Last accessed: 25 July 2018].

Akkanat, K 2012 *Communication and Interaction on Instagram. A Psychological Science Perspective.* Munich: GRIN Verlag.

Amedie, J 2015 The impact of Social Media on Society. *Advanced Writing: Pop Culture Intersections, 2.* Available at: https://scholarcommons.scu.edu/cgi/viewcontent.cgi?article=1002&context=engl_176 [Last accessed: 23/03/2019].

Bennato, D, Benhotman, H and Panconesi, A 2011 Processi di diffusione delle informazioni nelle reti digitali. Il caso Twitter. *Cultura e Comunicazione/ Culture and Communication*, 2: 72-78.

Bland, R 2009 The development and future of the Treasure Act and Portable Antiquities Scheme. In: Thomas, S and Stone P (eds.) *Metal Detecting and Archaeology*. Suffolk: Boydell & Brewer Ltd, pp. 63-86.

Bollwerk, E 2015 Co-creation's Role in Digital Public Archaeology. *Advances in Archeological Practice*, 3(3): 223-234.

Bonacchi, C 2012 Introduction. In: Bonacchi, C (ed.) *Archaeology and Digital Communication. Towards Strategies of Public Engagement*. London: Archetype Publications, pp. xi-xix.

Bonacchi, C, Bevan, A, Pett, D, Keinan-Schoonbaert, A, Sparks, Wexler, J and Wilkin, N 2014 Crowd-sourced Archaeological Research: The MicroPasts Project. *Archaeology International,* 17: pp.61–68. DOI: http://doi.org/10.5334/ai.1705

Bonacchi, C, Bevan, A, Pett, D, and Keinan-Schoonbaert, A 2015 Crowd- and Community-fuelled Archaeology. Early Results from the MicroPasts Project. In: Giligny, F, Djindjian, F, Costa, L, Moscati, P and Robert, S. (eds.) *CAA2014, 21st Century Archaeology. Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Paris*. Oxford: Archaeopress, pp. 279-288.

Bonacchi, C and Petersson, B 2017 Digital Co-production in Archaeology. Editorial, *Internet Archaeology*, 46. DOI: https://doi.org/10.11141/ia.46.1

Brock, T P and Goldstein, L 2015 Blogging the Field

School: Teaching Digital Public Archaeology. *Internet Archaeology*, 39. DOI: http://dx.doi.org/10.11141/ia.39.8

Baldassarre G 2018 Open Salapia: il progetto di archeologia pubblica dello scavo di Salapia (Trinitapoli). In: D'Eredità A. Falcone A (eds.) *Archeosocial. L'archeologia riscrive il web: esperienze, strategie e buone pratiche.* Mozzecane: DielleEditore, pp. 121-144.

Facebook 2018a, *The Vindolanda Trust*. Available at https://www.facebook.com/TheVindolandaTrust/ [Last accessed 13 August 2018].

Facebook 2018b, *VEiL - Visualising Engineered Landscapes*. Available at https://www.facebook.com/VEiL-Project/ [Last accessed 13 August 2018].

Griffiths, S, Edwards, B, Raimund, K, Labrosse, F, Miles, H, Moeller, K, Roberts, J, Tiddeman, B and Wilson, A 2015 Crowd-sourcing archaeological research: HeritageTogether digital public archaeology in practice. *Internet Archaeology*, 40. DOI: https://doi.org/10.11141/ia.40.7.3

Heinonen, K 2011 Consumer activity in social media: Managerial approaches to consumers' social media behavior. *Journal of Consumer Behaviour*, 10(6): 356-364. DOI: 10.1002/cb.376

Hodder, I 1999 *The Archaeological Process: An Introduction*. Oxford: Blackwell.

Instagram 2018, *VeiL Project*. Available at https://www.instagram.com/veil_project/?hl=it [Last accessed 13 August 2018].

Java, A, Song, X, Finin, T and Tseng, B. 2007 Why We Twitter: Understanding Microblogging Usage and Communities. In: *Proceedings of the 9th WebKDD and 1st SNA-KDD 2007 Workshop on Web mining and Social Network Analysis*. New York: ACM, pp. 56-65.

Miller, V 2008 New Media, Networking and Phatic Culture. *Convergence*, 14(4): 387-400. DOI: https://doi.org/10.1177/1354856508094659

MSU Campus Archaeology Program 2018. Available at http://campusarch.msu.edu/ [Last accessed 13/08/2018].

Perry, S and Beale N 2015 The Social Web and Archaeology's Restructuring: Impact, Exploitation, Disciplinary Change. *Open Archaeology* 2015, 1: 153-165.

Richardson, L-J 2012 Twitter and archaeology: an archaeological network in 140 characters or less. In: Bonacchi, C (ed.) *Archaeology and Digital Communication. Towards Strategies of Public Engagement.* London: Archetype Publications, pp. 15-24.

Richardson, L-J 2013 A Digital Public Archaeology? *Papers from the Institute of Archaeology*, 23(1). DOI: http://doi.org/10.5334/pia.431

Richardson L-J 2018 Ethical Challenges in Digital Public Archaeology. *Journal of Computer Applications in Archaeology*, 1(1): 64-73.

Rocks-Macqueen, D 2016 Digital Public Engagement through Social Media in Archaeology – How to Choose. *Present Pasts*, 7(1): 1. DOI: http://dx.doi.org/10.5334/pp.62

Traviglia, A, 2018 *VEiL Visualising Engineered Landscapes: an archaeological approach to unlock environmental resilience and sustainability in antiquity*. Available at http://www.unive.it/pag/18545/ [Last accessed 13/08/2018].

Twitter 2018, *VEiL Project*. Available at https://twitter.com/veilproject [Last accessed 13 August 2018]

Youtube 2018, *VEiL Project VPAI*. Available at https://www.youtube.com/channel/UCV2msywmejA-OkQ8hAtSYvbA [Last accessed 13 August 2018]

Walker, D 2014a Antisocial media in archaeology? *Archaeological Dialogues*, 21: 217–35.

Walker, D 2014b Decentering the discipline?Archaeology, museums and a social media. AP: *Online Journal in Public Archaeology*, Special Volume 1-2014: 77-102.

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Kieran Baxter
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VR and the Death of the Frame? Filmmaking in an Age of Immersive Technology

Kieran Baxter
Hornafjörður Research Centre
University of Iceland
kieranb@hi.is

Abstract

In light of immersive 360-degree and 3D capture technologies, which give the end-user retrospective control of the angle of viewing, the visual language of traditional filmmaking might appear fundamentally disrupted. This paper expands upon the relationship between film and virtual reality (VR) in the context of heritage interpretation. It explores the continuity between the two media, but also the disparate conventions and traditions that they draw upon. If we acknowledge that no medium is transparent then we must also consider how the practitioner's tools and decision-making affect media content and its meaning. While in VR these decisions are more likely to define the ways in which the audience can interact with content, in film the composition of the frame plays a significant role in channeling the audience's attention in a predetermined way. The frame is an integral component of photography and filmmaking. The continued relevance of such filmic conventions in a time of technological upheaval is a key question here. It is suggested that both filmmaking and VR will continue to offer unique and powerful tools for documentary storytelling in heritage interpretation, and that understanding the strengths of each will be important if we are to develop a well-considered visual toolkit that goes beyond the technological hype. As such, we test new norms of immersion and interaction afforded by recent developments in head-mounted display technology that might appear to be - and have certainly been promised to be - a paradigm shifting development in new media.

Keywords: virtual reality, filmmaking, new media, filmic language, embodiment

Introduction

This paper stems from the author's own research-practice in filmmaking and Virtual Reality (VR) content development, and represents an effort to better understand how these distinct media instill particular ways of seeing according to the cultural context of their creation and consumption (see Moser & Smiles 2005). As such, the focus here is not only the explicit methods involved in each case but also the implicit meanings behind film and VR. Gauntlett (2018) reminds us of the pervasive ways in which new media - if left unchecked - can inadvertently affect our everyday lives, but also remains optimistic that technological tools can act as catalysts to positive social change if used creatively. Such issues and considerations surrounding new media bring to bear upon the field of visualisation for built heritage in general, and in particular where public outreach and communication work aims to reach general audiences who are not versed in the specific visual syntaxes that are understood within archaeology. As this discussion relates to a visual cultural domain, the arguments are supported using a combination of critical

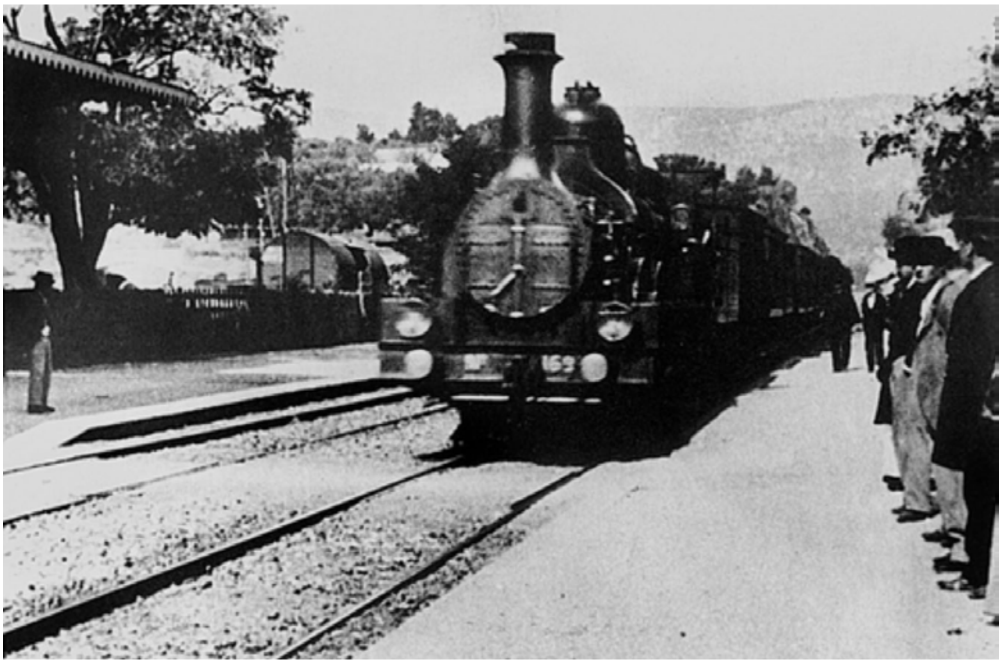

Figure 1. Still from The Arrival of the Train at the Station, Auguste and Louis Lumière, 1896, public domain image.

theory and examples from the author's creative research-practice. Insights can thus be gained through practice - particularly relating to the tensions between lived experience and visual media - that would be difficult to access through purely textual enquiry (see Cazeaux 2006; Biggs 2004).

At the outset the origins and "guiding myths" of film and VR are discussed and the notion of realism is problematised in relation to the two forms of new media. The significance of embodied engagement will be explored in terms of how this relates to phenomenological understandings of place, and the tensions between simulation and experience. In order to understand how these issues relate to recent technological developments, the types of embodied engagement and levels of interactivity that are afforded by current motion tracked VR systems will be expanded upon. Finally, two practical examples from the author's own research-practice in film and VR are discussed in terms of how the creative decisions made were affected by the affordances of each medium. The aim is to consider the relationship between creative practice and new media technology in the context of built heritage visualisation.

The Guiding Myths of Film and VR

Bazin (1967) proposed that the "guiding myth" behind the early development of film was the notion of a "total reality", that is to say that the on-screen world could one day be indistinguishable from the real. For Bazin this myth would culminate in "an image unburdened by the freedom of interpretation of the artist or the irreversibility of time" (1967: 21). Although this was meant only as an originating ideology, if there has ever been an incarnation of Bazin's myth then it lies in the notion of actuality film, which was pioneered by the brothers Auguste and Louis Lumière.[1] Unlike their contemporaries, who embraced the illusory characteristics of the new medium, they attempted to show naturalistic scenes unmediated by artistic influence and artificial narrative. They are most renowned for their short film The Arrival of the Train at the Station (L'Arrivée d'un train en gare de La Ciotat Auguste, 1896; figure 1), which reportedly appeared so true to life that it sent frightened audiences running from theatres.

Except of course that it never did. In reality audiences of the time were not "naive spectators" as has sometimes been imagined but were able to distinguish between the real-world and the artifice of the projected image (Gunning 1989: 116). The attraction

1 The Lumière brothers produced early cinematic equipment and naturalistic film content at the turn of the Twentieth Century, a time when stage magicians were also widely adopting the new technology, notably including visual effects film pioneer Georges Méliès. For a detailed account of this historical continuity between stage and screen see Barnouw (1981).

Figure 2. Using a HMD and motion controllers, photograph by the author, 2017

of cinema then lies in the aesthetic of the uncanny, or in the tensions of a partial reality, rather than in any manifestation of Bazin's total reality. This is evident in the explicitly artificial visual language of film today where constructs such as cuts, dissolves and montage - that have no equivalence outside of the film world - form part of a widely accepted visual syntax that is integral to the medium.

Manovich (2001) later drew parallels between Bazin's guiding myth and the aspirations of VR technology. In light of technological developments in new media he makes the provocative claim that "the promise of Bazin's 'total realism' appears to be closer than ever" (2001: 189). Certainly the "yearning" for a perfect facsimile of the real, facilitated by VR, proliferated decades before Head-Mounted Display (HMD) technologies had the comfort, rendering capabilities, and accessibility that they have today (Penny 1993: 18; Gillings 2005: 224). While Bazin's total reality might be a useful guiding myth, we can fully expect to see, as we have seen in film, that the emerging visual language of VR is defined as much by the artifice of the virtual as it is by integrity to the real.

With this in mind, instead of measuring film and VR by their proximity to the real it might be more useful to consider the ways in which they exploit the senses. The stereograph, popular in the late nineteenth century, used stereo vision to give a sense of "presence" in what Gurevitch describes as a "proto-cinematic spectacular attraction" (2012: 243). Gurevitch compares a stereo-card depiction of a train approaching the viewer along a vertiginous bridge - produced by Benjamin Kilburn sometime in the late 1800s - to the film The Arrival of the Train at the Station. The suggestion here is that the way in which the stereograph and the motion picture call upon bodily engagement - through stereo depth perception on the one hand and the persistence of vision on the other - marked a radical departure from the apparent indexicality of the photograph, but also afforded both media the attraction of the spectacle. It is not the intention here to draw a direct parallel between VR and the stereograph - as stereo vision is only one element of modern-day VR - but rather to highlight that a play upon the senses in itself lends an attraction, and an uncanny type of realism, to new media. Where VR departs from film and stereography is with the augmentation of bodily interaction, facilitated by software feedback loops and motion control hardware.

Virtual Experience of Place?

What then do we mean by the seemingly oxymoronic virtual reality? While the term VR has been used in archaeology to refer to all types of computer gen-

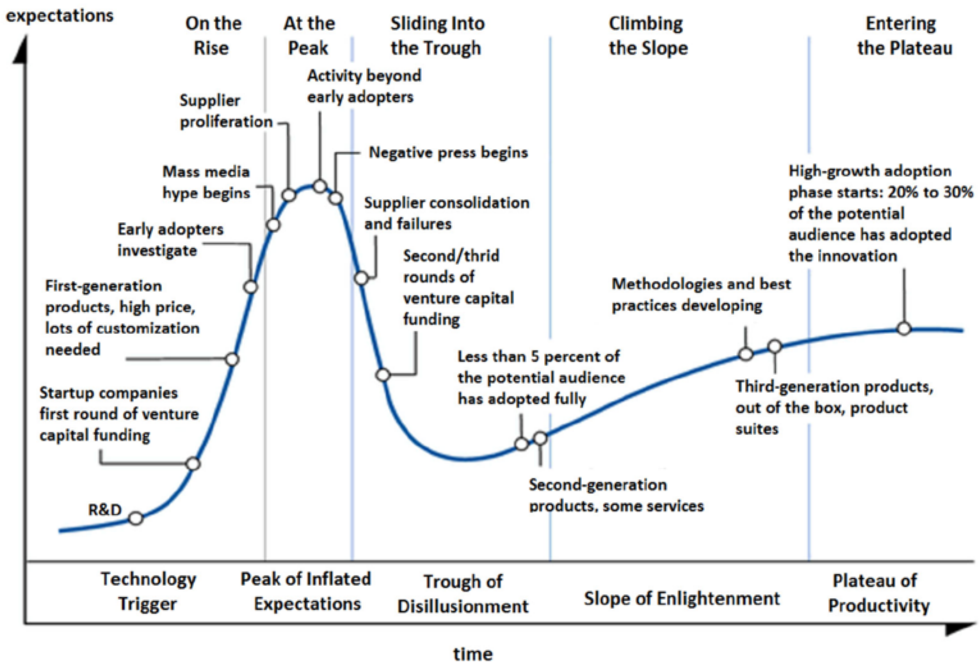

Figure 3. General Gartner Research's Hype Cycle, diagram drawn by Olga Tarkovskiy (CC BY-SA 3.0), 2013.

erated imagery that tend towards "realistic" representation, today it more often refers specifically to the embodied interaction enabled by HMD technologies and motion control devices (figure 2). "The notion of the real" - Coyne states - "is intimately connected with embodiment" (1999: 49). Just as we might pinch ourselves to check if we are dreaming, as we look around in VR the live feedback loop that we receive convinces us in part that what we are seeing is real. This "reality check" is a type of reality illusion that is quite distinct from photorealism. Where in the past illusions of reality have primarily relied upon "visual fidelity", Manovich argues that digital interactive media "construct the reality effect on a number of dimensions [including] bodily engagement with a virtual world (for instance, the user of VR moves the whole body)" (2001: 182). As such we can say that VR as we know it today is by its very nature interactive. To remove that bodily interaction would be to remove the primary illusion upon which the virtual reality is based.

The interactive and embodied nature of VR could then, at least in principle, make the medium a useful tool to explore built heritage - and landscape archaeology in particular - from a phenomenological standpoint. Brück suggests that modeling architecture and landscape in VR could be useful in this regard because it "overcomes the abstracted perspective of two dimensional mapping" (2005: 52). By simulating a human perspective we might assume that it is possible to "see" what it is like to move through an environment just as we might consider the experience of walking through a real place. Gillings has problematised such a view however pointing out that, beyond its use as a tool to assess chorography from ground level, VR should not be considered a proxy for - much less equivalent to - embodied experience of place (2005: 233). This is in part because the model is not the place, but also because VR systems - despite their ever-increasing sophistication - engender a specific way of seeing that remains far from an unmediated type of embodiment. Thomas has critiqued the affordances of VR modeling on both counts, pointing out the contradiction of using a simulation - representing only an illusion or the appearance of things - to access the thing itself, as well as the shortcomings of prioritising vision over multi-sensory experience (2004: 198-201). In order to bridge this gap between the lived experience of place and the types of perception that are allowed by a virtual model, we should consider more closely the nuance and complexity of human engagement rather than place undue expectations on improvements in VR hardware and software. As Coyne puts it:

> "The ambitions of VR remind us that the real is that which resists representation. It is ineffable." (Coyne, 1999: 269)

A number of suggestions have been made as to how we might attempt to imbue digital models with the sometimes "ineffable" experiential, socio-political and aesthetic dimensions that we can attribute to the real. At the outset, we must acknowledge that improvements in technology alone will not do this by default. This can sometimes seem contra to a prevailing culture of techno-optimism which permeates digital practices. What Huggett terms "technological fetishism" within archaeological practice may be driven by the lure of the "state of the art" (2004: 88) but it is also entwined - in potentially sinister ways - with the technology industries that generate both supply and demand for new hardware and software (see Perry & Taylor 2018: 17). The influence and vested commercial interest of these industries should not be overlooked. Perry and Taylor question the way in which technologies are often uncritically labeled as "emergent" - sometimes regardless of how long they have actually been around for - and point to where the "Gartner Hype Cycle" has been used to illustrate how the perceived significance of a technology can be driven by hype rather than due consideration of its actual capabilities (2018: 14; figure 3). Recent developments in VR are no exception to this, with claims of proximity to the real not only being often exaggerated but also missing the point that lived experience cannot be defined in such simple terms as resolution or frame rate.

How then might we strive to make more "real" - or at least more meaningful - digital experiences given the uncanny nature of virtual environments? As Jeffrey points out, while it is certainly possible to gloss over the "weirdness" of the digital object by focusing on narrative realism and thus exploiting the "suspension of disbelief" - for example through gamification - this should be approached cautiously in the context of digital heritage (2015: 150). An alternative is to focus on the co-production of digital artefacts and the adoption of more reflexive approaches to practice which respond to, and make more transparent, the processes and multiple voices behind digital media (Jeffrey 2015; Dallas 2015, Watterson & Hillerdal 2020). In doing so virtual spaces may be enriched with a sense of authorship and socio-political context in much the same way that real world artefacts and places are. In addition, solutions might be sought in creative practice, either through collaboration with artists, or by the adoption of creative approaches within digital heritage (Gant & Reilly 2018; Perry & Taylor 2018; Watterson 2015).

As a media practitioner working with and for archaeologists, the author's research aims to explore the role of creative practice in creating visualisations that communicate both the feelings and meanings surrounding archaeological sites. Central to this enquiry are the tensions between the lived experience of place on the one hand and the virtuality of new media on the other. Before discussing this research-practice, the technical affordances of VR technologies will be expanded upon. As noted at the start of this section, the term VR has tended to be used within archaeology as a broad definition encompassing a variety of types of engagement with computer generated graphics. The aim of this paper is to better understand what the creative toolkit looks like in the specific context of current VR systems, where embodied interactions are afforded by motion tracking technology. The following section will define those affordances in more detail.

Degrees of Freedom in VR

While all modern VR systems utilize motion tracking technology to provide visual feedback as the user moves their head, in practice this embodied interaction comes in different levels. At its most fundamental, VR allows the viewer to look around freely within 360-degrees of view. In technical terms this is known as three-degrees-of-freedom, in reference to the three rotational axis allowed by this type of movement. Additional levels of interaction allow a response to translational (lateral) movement of the HMD through space, as well as the augmentation of handheld motion control devices and other input and feedback loops. The addition of the three translational axis of movement to the three rotational axis means that these more sophisticated systems are referred to as six-degrees-of-freedom. These levels of interaction can also be broadly categorised as either Cinematic VR (CVR), where interaction is limited, or fully interactive VR where more extensive engagement with the virtual world is available.

Cinematic VR

Where in film the action takes place within a predetermined frame of view, CVR allows the viewer to look around from a fixed position in 360-degrees, albeit with limited interaction with the environment. This category includes both monocular and stereo 360-degree films when experienced through a headset, as well as 3D environments where the viewer is unable to fully navigate the space, and events take place according to a predetermined narrative. The compromise of CVR is that while the user is free to look in any direction, if their attention is to be directed towards important narrative elements it must be guided without the use of the frame boundaries available in film. In Mateer's (2017) review of the current state of CVR it is noted that, despite fundamental differences between the two media, some of the established methods used to guide the audience's attention in film can be translated for VR content:

"Film directors have developed several means by which they can control audiences and subliminally guide viewer gaze around the frame [...] Although some of these rely strictly on the limits imposed by a finite 'window' into the environment (i.e. the film frame), several are applicable in a CVR context […]" (Mateer 2017: 21-22)

For example, Nielsen et al. (2016) conducted an experiment where different methods were used to guide a viewer towards the significant action within a short CVR piece. In one version the viewer's gaze was artificially altered to face certain directions at certain times. In another, a glowing firefly moved between points of interest in a way which was more naturalistic and consistent with the virtual world. While caution should be taken in seeking a general formula for new media practice - at the risk of overlooking the cultural contexts in which media operate - in this case it was found that the latter method of guiding the viewer's attention without interfering with the freedom to look around the scene was most successful. This might suggest an expectation for VR interfaces to be interactive in some way, even within the constraints of CVR.[2]

2 In their experiments with various immersive forms of art installation Head & Sujir note that the use of a VR headset made people want to actively engage with the content (2020).

Fully Interactive VR

Taking engagement with the virtual world further, in fully interactive VR the user is able to interact to a greater degree with the environment and to move around the space more freely, sometimes assisted by navigation tools activated via the handheld controllers for example. This freedom of movement is a particularly powerful aspect of the VR medium in the context of built heritage as the notion of exploration is an important part of our engagement with heritage sites in the real world. This also represents a shift away from the relatively passive role of the observer in CVR - inherited from the paradigms of film - to a more participatory role that fully exploits the interactive capabilities of the new medium.

An example where this is done successfully is the MasterWorks project published by CyArk in 2018, which presents a variety of content based around four UNESCO world heritage sites in a VR environment.[3] Central to the virtual experience is the ability to navigate around fully three-dimensional models of the four sites, produced using LiDAR and photogrammetry. While there are limits to the navigational scope of the models, the terrain and environment are extensive and featureful enough that exploring the sites by moving around using the HMD - aided by teleportation via the handheld controllers - is a significant part of the content in its own right. While the sites are contextualised with information on the archaeological interpretation and related portable artefacts, the virtual experience has not been fully gamified in that the viewer is free to explore outside of any predetermined narrative or goals. What makes this approach both accessible and relevant to the content is that it enriches the virtual interactions while mimicking the ways that we might explore such sites as a visitor.

Exploring Theory in Practice

Having introduced some of the technical affordances of VR, this section will report on examples of research-practice that have navigated some of the issues discussed here. The aim is to examine how

3 Available to download at: http://www.masterworksvr.org/

Figure 4. Ground-based filming for The Caterthuns film, photograph by Kieran Duncan, 2013.

creative decision making during production of the practical outcomes was affected by the limitations and affordances of the respective media. As a point of comparison the first example is a short film created during the author's PhD research, while the second is a VR environment developed at the 3DVisLab at the University of Dundee. Both projects aimed to create an emotive sense of place based upon real-word heritage environments. This sense of place is considered to be an important platform for communicating archaeological knowledge because it can be shared by specialists and non-specialists alike. Beyond this the experiences surrounding heritage sites can be an integral part of their archaeological interpretation. Despite the common aims of the two projects, the means by which real-world feeling and atmosphere was translated into digital content was markedly different in each case. This was governed partly by the situation of the sites themselves but largely by the disparate affordances of the two media used.

The Caterthuns Research Film

The Caterthuns is a short experimental film that uses aerial footage and digital models to tell the story of a pair of Iron Age hillfort sites in the region of Angus in Scotland.[4] The aim of the film was to connect a sense of the landscape as it can be experienced from the ground with an impression of the sites' architecture - which is best seen from the air - along with their archaeological interpretations. To achieve this the film prioritised photographic composition in the field. By allowing the photographer/filmmaker to respond creatively to their own experiences, the intention was to allow them to influence the resulting imagery. The film is made up of footage taken from the ground, as well as kite aerial photography, drone footage and photography taken at higher altitudes from a light aircraft. While photogrammetry models were used for large parts of the film, these were adapted as a means to animate sequences of pho-

4 The film outcome can be viewed online at: https://www.vimeo.com/147173130

Figure 5. Stills from The Caterthuns short research film by the author, 2016.

tographs that were composed in the field, meaning that the final results remained closely related to the original imagery. This imagery was collected in all conditions, at different times of the year and different times of day, requiring multiple visits and intensive fieldwork spread over many months. Spending extensive time in the field was necessary to build an in-depth impression of the landscape and in order to approach the type of insider's view which Ingold termed the "dwelling perspective" (1993: 59). The variety of methods used for photography and filming also represented a conscious decision to engage with the sites in different ways and thus expand upon the ways of understanding the landscape through those experiences (figure 4). This approach has been explored in previous practice-based collaborations that prioritised time in the field (see Baxter 2014a; Waterson et al. 2014).

To allow the experiences of the fieldwork to filter through to the film outcome, creative decisions were made in response to aesthetic considerations such as mood and atmosphere. The choice of framing was a key component to this and played a significant part in the resulting short film (figure 5). It was noted that while some shots were carefully planned and involved returning to re-shoot a particular angle in certain lighting conditions for example, others were more spontaneous and intuitive. This was particularly true of photography from the fast-moving light aircraft where, although careful route planning was undertaken pre-flight, photographs were often composed within a matter of seconds. Some of the strongest compositions were unplanned, and made in response to the particular conditions at the time of shooting. Making these creative decisions in-situ was a key way in which the lived experiences of the photographer/filmmaker were allowed to influence the visual results of the film. This relationship between multi-sensory experience and image is made possible through the creative use of photography (see Shanks 1997: 100), with the act of framing being a crucial part of this process. Collecting this photographic material in an open-ended way acknowledges the new understandings which emerge from the process of engagement during fieldwork and encourages these insights to guide the visual outcome, itself a product of the interaction between the landscape, the practitioner and their tools rather than a "projection" of a preconceived image (Ingold 2011: 178; see also Gosden & Malafouris 2015).

The animated movements of the camera were also carefully considered and executed using a combina-

Figure 6. The underwater survey team conducting photogrammetry on the HMS Hampshire, photograph by Marjo Tynkkenen, 2016

tion of filming and digital synthesis from still photographs. In practical terms these movements help to reveal the three dimensional form of the landscape (via parallax) but also afford an impression of flight above, and passage through, the landscape. Castro describes how aerial tracking cinematography can evoke "emotion" linked to both the feeling of flight and discovery of the landscape below (2013: 125).[5]

As such the pacing and gesture of these lines of movement were carefully composed - again drawing influence from Ingold (2007) - to bring the viewer on a journey around key features of the sites. As the camera moves the frame is constantly changing, revealing more or less of the landscape. In cinema framing is an important tool which can act not only as a passive conduit for the image but as an expressive medium for the filmmaker's intentions (see O'Rawe 2011). Here the frame is used to gradually build up an impression of a multifaceted landscape, drawing attention to how the sites change as they are seen from the ground and from the air, as well as over time.

Some sequences take advantage of the novel possibilities afforded by the process of synthesising digital imagery. These include a shot which ascends from a close-up of a human figure to a high aerial view over both sites, designed to "ground" the otherwise abstracted aerial perspective to a relatable sense of scale and presence within the landscape (see Baxter 2014b). Two other "impossible" shots that were made possible through digital synthesis transition between summer foliage and winter snow cover, showing the changing face of the landscape throughout the seasons. These "time-lapse" shots are important because they draw attention to the ways in which - unlike a digital model - the landscape is constantly undergoing change, revealing unexpected facets and forms. The transparent artifice of these shots is also intended to implicitly acknowledge the process of production behind the film because the audience are aware that these transitions can only exist in the filmic world. Similarly, speculative reconstructions of lost structures - modelled in collaboration with archaeological reconstruction artist Alice Watterson - are rendered photorealistically but fade in and out of view to emphasise that they have been artificially superimposed.[6] Given the uncanny nature of filmic visual language discussed earlier in this paper, we can consider that photorealism is not necessarily at odds with the speculative nature of these reconstruc-

5 Castro is describing the film In an Airship over the Battlefields (En dirigeable sur les champs de bataille), produced by Lucien Le Saint in 1919, which made early use of the aerial tracking shot not long after the Lumière brothers also first began to experiment with filming from a moving platform.

6 The deliberate use of a dissolve effect to visually separate speculative reconstructions from the modern-day landscape while drawing the viewer's attention to "the artificial nature of the imagery" was discussed in a previous research-practice project (Baxter 2014a).

Figure 7. Still from HMS Hampshire VR environment developed at the 3DVisLab, University of Dundee, 2017.

tions (see Earl 2013). In the context of film there is an implied authorship understood by an audience who are aware that what appears on screen is some combination of artificial illusion and natural reality. This is reinforced by the format of The Caterthuns which is framed as the result of a creative process, revealing only a partial impression of a dynamic and multifaceted landscape which extends beyond the frame.

HMS Hampshire VR environment

HMS Hampshire is a World War One shipwreck and war grave located around three kilometres offshore of Marwick Head in Orkney. In 2016 a photogrammetric survey of the wreck was carried out under special permit by a team of divers using underwater cameras, high powered lights and technical diving equipment (see Macdonald et al. 2020; Rowland & Hyttinen 2017). Photogrammetry data from the survey was developed at the 3DVisLab at the University of Dundee to create a VR experience with the aim of allowing exploration of the site within an impression of what it is like to dive on a historic shipwreck. The process of developing the content from data collection to the final outcome was radically different from The Caterthuns film on two counts. Firstly, access to the site is limited due to the shipwreck's depth, remote location and status as a war grave. This makes extensive and repeat visits for photography and filming logistically challenging at best, and impossible for those without technical diving skills. An experiential sense of place must be based on footage and first-hand accounts, in this case through collaboration with members of the underwater survey team (figure 6). In addition, while photographic framing in the field was integral to The Caterthuns project, the photogrammetry data used in this case was captured with the aim of complete coverage of certain study areas of the shipwreck. This type of survey is ideal for VR content as it allows the viewer to retrospectively explore the scene from any angle.

Visual cues were then added to the survey data to recreate the mood and atmosphere of the real-world site. This was made complicated by the fact that most of the development team and the vast majority of end users will never visit a subsea shipwreck, raising questions around what it means to recreate a realistic experience in the context of an activity (technical diving) which is far beyond everyday experience for most.[7] This perhaps made it more likely that compro-

7 Similar epistemological questions can be applied

mises were made, for example where visibility was extended beyond the limits of the real-world environment to reveal more of the shipwreck. In addition, there is a tension between the realities of diving at the site and the aspirations of the data gathering process. Dynamic elements such as sea life and water visibility - while integral to the experiences of the subsea environment – hinder data collection and must be mitigated for, or even purposely removed from the data. Working with survey data that was collected with metric fidelity and comprehensiveness in mind was in sharp contrast to the photographic approach adopted for The Caterthuns film. For the HMS Hampshire project there was a point of departure - when the survey data is used to inform a visualisation aimed at communication to non-specialists rather than scientific analysis - beyond which portraying an authentic sense of place was deemed of equal importance as preserving the integrity of the data.

In light of this, certain elements were added based on the appearance of the underwater footage and the accounts of the survey team. As the viewer moves around the space, foreground details are illuminated by virtual lights that are attached to the handheld motion controllers emulating torch light. Floating particles were also added that both emulated the appearance of the sub-sea environment and also provide a point of reference in terms of depth and volume in the virtual space, reinforcing the movement of the HMD (figure 7). A fog effect simulates the way in which seawater occludes light, although as previously noted the viewer is allowed more visibility than is likely to be seen at the real-world site. These naturalistic elements were designed to encourage the viewer to explore the scene through their bodily interaction, as moving the HMD and motion controllers reveals more or less of the environment.

Rather than viewing the photogrammetry data as a digital artifact distanced from the real thing, here we are using VR to present a historic shipwreck in the context of the experiences that could be expected when diving on such a site. This is important because it affords the viewer a sense of discovery, but critically a sense of presence, an impression that the virtual model relates to a real world heritage environment that could be visited, albeit in this case with great difficulty due to the site's location and protected status. Unlike at the Caterthuns which are relatively easily visited there is a remote access issue here, with VR being the closest that both specialists and non-specialists are likely to come to visiting the HMS Hampshire. This project explored how this can be done in a way that respects the integrity of both the underlying data and the aesthetics of the site's situation.

Conclusion

Despite the tensions between the reality of lived experience and the virtuality of new media it is possible for some aspects of what Jeffrey terms the "aura" of physical sites and artefacts to transmit to their simulated counterparts (2015: 146). Creative approaches to practice leave space for the invisible elements of real-world places to influence the visual, for example through evocative mood and atmosphere.[8] Throughout the practical examples explored here we have seen how the creative toolkits that facilitate this differ between media. The inherently interactive nature of VR sets it apart from film where the viewer's attention is guided by the way in which footage is framed. In film, framing can be used as an expressive tool to tell the story not only of the on-screen elements but also of the experiences of the photographer/filmmaker and the broader landscape that lies beyond the frame. In VR other methods can be used to reintroduce experiential elements of the real-world environment into the virtual space. These should reinforce the interactive nature of VR engagement where possible, while also drawing from real-world observation and experiences.

The guiding myths that drive the development of new media do not necessarily define the visual languages and practices that are later adopted. A modern incarnation of Bazin's notion of the guiding myth might be seen in the Gartner Hype Cycle (figure 2), where new technologies must pass through a "peak of inflated expectations" before eventually settling onto a "plateau of productivity". As researchers and

more generally to archaeology and digital modelling where knowledge is created through specialist practices which are unavailable to many (see Dallas 2015; Carter 2017).

8 Shared experiences of landscape may be evoked through atmosphere (see Jóhannesdóttir 2010), which may comprise elements beyond the visual, such as soundscape for example (see Gant & Reilly 2018).

practitioners we have a responsibility to see past this cycle, particularly where there is vested commercial interest behind the hype, and to concentrate instead upon the "slope of enlightenment". Here the truly novel benefits of a new medium can be exploited, and emerging tools can find a place within the existing toolkit for storytelling that is available to heritage professionals and creative practitioners. Understanding these new affordances and their implications is important if we are to ensure that heritage visualisation practice is theoretically grounded (Huvila & Huggett 2018). It is after all the ways in which we critically and creatively adapt digital media, not the technology itself, that will determine our ability to meaningfully visualise heritage environments. VR represents a radical departure from film not because it is a step closer to a total reality but because the embodied interaction that it facilitates represents a novel form of engagement with virtual places and artefacts. While the possibilities that this presents have great promise in the field of built heritage visualisation they do not threaten to overtake the paradigms of filmic language. Instead we can expect VR to stand alone as a new and alternative medium with its own distinct affordances.

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Reference

Barnouw, E 1981 *The Magician and the Cinema*. New York, Oxford University Press.

Baxter, K 2014a Jarlshof Lost and Found: Low altitude aerial photography and computer-generated visualisation for the interpretation of the complex settlement remains found at Jarlshof, Shetland. *Internet Archaeology* 36.

Baxter, K 2014b Grounding the Aerial: The Observer's View in Digital Visualisation for Built Heritage, *Electronic Visualisation and the Arts: proceedings of the EVA 2014 conference*, London, pp. 163-170.

Bazin, A 1967 (translated 2005) *What is Cinema?: Essays selected and translated by Hugh Gray. Volume 1*. Berkeley, University of California Press.

Biggs, M 2004 Learning from Experience: approaches to the experiential component of practice-based research. *Forskning, Reflektion, Utveckling* 6(12): 7-21.

Brück, J 2005 Experiencing the past? The development of a phenomenological archaeology in British prehistory. *Archaeological Dialogues* 12(01): 45-72. DOI: 10.1017/S1380203805001583

Carter, M 2017 Getting to the point: Making, wayfaring, loss and memory as meaning-making in virtual archaeology. *Virtual Archaeology Review*, 8: 97-102. DOI: 10.4995/var.2017.6056

Castro, T 2013 Aerial Views and Cinematism, 1898-1939. In: M Dorrian and F Pousin (eds.) *Seeing From Above: The Aerial View in Visual Culture*. London, I. B. Tauris: 118-133.

Cazeaux, C 2006 Interrupting the artist: theory, practice and topology in Sartre's aesthetics. Macleod & L Holdridge (eds.) *Thinking through art: reflections on art as research*, London, Routledge, pp. 40-50.

Coyne, R 1999 *Technoromanticism: Digital Narrative, Holism and the Romance of the Real*. Cambridge, MIT.

Dallas, C 2015 Curating Archaeological Knowledge in the Digital Continuum: from Practice to Infrastructure. *Open Archaeology 2015*, 1: 176-207.

Earl, G 2013 Modeling in archaeology: computer graphic and other digital pasts. *Perspectives on Science*, 21(2): 226-244.

Gant, S & Reilly, P 2018 Different expressions of the same mode: a recent dialogue between archaeological and contemporary drawing practices, *Journal of Visual Art Practice*, 17(1): 100-120.

Gauntlett, D 2018 *Making is Connecting: The social power of creativity, from craft and knitting to digital everything, Second expanded edition.* London, Polity.

Gillings, M 2005 The Real, the Virtually Real, and the Hyperreal: The Role of VR in Archaeology. Smiles S and Moser S (eds.) *Envisioning the Past: Archaeology and the Image*, London, Blackwell, pp. 223-239.

Gosden, C & Malafouris, L 2015 Process archaeology (P-Arch). *World Archaeology*, 47(5): 701-717.

Gunning, T 1989 An Aesthetic of Astonishment: Early Film and the (In)Credulous Spectator. *Art and Text,* 34: 114-133.

Gurevitch, L 2012 The Birth of a Stereoscopic Nation: Hollywood, Digital Empire and the Cybernetic Attraction. *Animation: An Interdisciplinary Journal,* 7(3): 239-258.

Head, A & Sujir, L 2020 Researching virtual, augmented and mixed realities, or how the Elastic 3D Spaces project emerged from an outdoor projection event. Menotti G & Crisp V (eds.) *Practices of projection: histories and technologies*, Oxford, Oxford University Press. pp. 155-172.

Huggett, J 2004 Archaeology and the new technological fetishism. *Archeologia e Calcolatori*, 15: 81-92.

Huvila, I & Huggett, J 2018 Archaeological Practices, Knowledge Work and Digitalisation. *Journal of Computer Applications in Archaeology*, 1(1): 88–100.

Ingold, T 1993 The Temporality of the Landscape. *World Archaeology,* 25(2): 152-174.

Ingold, T 2007 *Lines: A Brief History*. London, Routledge.

Ingold, T 2011 *Being Alive: Essays on Movement, Knowledge and Description*. London: Routledge.

Jeffrey, S 2015 Challenging Heritage Visualisation: Beauty, Aura and Democratisation. *Open Archaeology,* 2015(1): 144-152.

Jóhannesdóttir, G 2010 Landscape and Aesthetic Values: Not Only in the Eye of the Beholder. Benediktsson K and Lund K (eds.) *Conversations with Landscape,* New York, Routledge, pp. 109-124.

Macdonald, R, Wade, B, Turton, E, Haynes, P, Crofts, D and Rowland, C 2020 *HMS Hampshire 100 Survey 2016, Survey Report 2020*. University of Dundee, UK.

Manovich, L 2001 *The Language of New Media*. London, The MIT Press.

Mateer, J 2017 Directing for Cinematic Virtual Reality: how the traditional film director's craft applies to immersive environments and notions of presence. *Journal of Media Practice,* 18(1): 14-25.

Moser, S & Smiles, S 2005 Introduction: The Image in Question. Smiles S & Moser S (eds.) *Envisioning the Past: Archaeology and the Image,* London, Blackwell: 1-12.

Nielsen, L, Møller M, Hartmeyer S, Ljung, T, Nilsson N, Nordahl R, and Serafin, S 2016 Missing the point: an exploration of how to guide users' attention during cinematic virtual reality. Kranzlmüller, D & Klinker, G (eds.) *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology,* pp. 229-232.

O'Rawe, D 2011 Towards a poetics of the cinematographic frame, *Journal of Aesthetics & Culture*, 3(1).

Penny, S 1993 Virtual Bodybuilding. *Media Information Australia*, 69: 17-22.

Perry, S & Taylor, J S 2018 Theorising the Digital: A Call to Action for the Archaeological Community. Matsumoto M & Uleberg E (eds.) *In Oceans of Data: Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology*. Oxford, Archaeopress, pp. 11-22.

Rowland, C & Hyttinen, K 2017 Photogrammetry in Depth: Revealing HMS Hampshire. *Electronic Visualisation and the Arts: proceedings of the EVA 2017 conference*, London: 358-364.

Shanks, M 1997 Photography and Archaeology. In: Molyneaux B (ed.) *The Cultural Life of Images: Visual Representation in Archaeology,* London, Routledge: 73-107.

Thomas, J 2004 *Archaeology and Modernity*. London, Routledge.

Watterson, A 2015 Beyond Digital Dwelling: Re-thinking Interpretive Visualisation in Archaeology. *Open Archaeology 2015*, 1(1): 119–130.

Watterson, A, Baxter, K and Watson, A 2014 Digital Dwelling at Skara Brae. Russell I and Cochrane A. (eds.) *Art and Archaeology: Collaborations, Conversations, Criticisms,* London, Springer: 179-195.

Watterson, A and Hillerdal, C 2020 Nunalleq, Stories from the Village of Our Ancestors: Co-designing a Multi-vocal Educational Resource Based on an Archaeological Excavation. *Archaeologies: Journal of the World Archaeological Congress 2020.*

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Zachary Batist
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Documenting archaeological knowledge construction as information practices

Zachary Batist
Faculty of Information,
University of Toronto
z.batist@mail.utoronto.ca

Abstract

Archaeology is a complex and communal undertaking that brings together people with varied backgrounds, who mobilize a wide range of tools and expert knowledge to assemble the archaeological record. In recognizing objects of interest and characterizing their significance through encoded disciplinary language (i.e. through data construction and other forms of scholarly communication), we situate our tacit, local experiences within an archaeological epistemic culture, or common modes of reasoning. Communication among archaeologists is therefore considered as a process of enculturation, whereby a shared understanding of the pragmatic conditions and expectations that underlie a record's construction facilitates its continued use by others.

This paper presents the preliminary results from my doctoral research, which is an attempt to better understand this archaeological epistemic culture, and to develop information infrastructures that facilitate the interoperability of archaeological data across research contexts. By observing archaeologists as they work, which includes affixing GoPro action cameras to their foreheads in order to obtain first-person perspectives, the physical, cognitive and communicative processes that comprise common fieldwork practices are formally identified and related. These observations are integrated with interviews and analysis of recording practices in order to better understand individuals' affective roles within their socio-technical research environments, as well as the communicative processes (i.e. documentation, representation and mediation) that enable research to be distributed among archaeologists and across various settings. In sum, I trace the relationships among archaeologists, their tools, the ideas they draw from, and the archaeological record itself, as knowledge is constructed under realistic and social conditions.

Keywords: archaeological practice; meaning-making; collaborative practices

Introduction

The push towards reflexive archaeological practice has led to rich discussions concerning the ways in which archaeological knowledge is constructed and presented within contemporary research environments. The seemingly stable and consistent values stored in a database, spreadsheet, photograph or schematic are generally recognized to be more than just static lumps of bits on a hard drive; they actually represent dynamic stories of archaeological practice that occurs within uneven social landscapes, populated by people holding varied perspectives, as well as objects and ideas that undeniably and inescapably shape what we know, and how we know, about the past (Lucas 2012; Wylie 2017). Understanding how this occurs, however, requires a shift in perspective that focuses an analytical gaze back upon the archaeological process.

The practical ways in which archaeologists navigate such epistemically-complex disciplinary landscape in order to say authoritative and meaningful things about the past can be analyzed in a variety of ways, ranging from informal discussion of generalized disciplinary tendencies, to highly methodological analysis of specific archaeological practices; however closer examination of what archaeologists actually do 'close to the metal' – that is to say, what they actually do in their day to day work, as opposed to what they think or say they do – may more effectively capture the intricacies and taken for granted tendencies that fade into the background, which encompass collectively held assumptions and norms. Such investigations that highlight the needs and outcomes of archaeological practices from various stakeholder perspectives may better inform the development of more effective information infrastructures – the set of organizational practices, techniques and social norms – that support archaeological research in practice.

This paper examines a series of specific episodes of archaeological fieldwork through activity theory, situated cognition, and distributed cognition approaches. Each has its own benefits and limitations, which will be discussed in general terms and with regards to their potential application examining archaeological research practices.

Framing Scholarly Practice

This work draws from sociology of scientific knowledge by examining scholarly research as cultural practice, or ways of understanding the world through a complex series of physical and conceptual interactions between humans and their objects of interest (Knorr-Cetina 1999; Pickering 1992a). This is accomplished by othering scholars and examining them as part of professional communities, whose members share common material engagements, modes of communication, organizational structures and conceptual norms. This makes it possible to document and analyze scholarly work as a series of improvised, continuous and community-driven practices, involving interactions among people, objects and ideas (i.e. socio-technical interactions). However, various methodological frameworks, including activity theory, situated cognition and distributed cognition, may be applied to examine research practices in different ways. Each of these approaches yield different kinds of insights, and it is important to consider their affordances and limitations when conducting methodologically rigorous reflexive research about archaeological practice and knowledge production.

Activity Theory

Activity theory is a theoretical framework that breaks down and carefully considers the relations that comprise goal-directed practical activities. Activities are comprised of subject-object relations, whereby objectives direct a series of actions conducted by subjects, who mobilize various mediating artefacts in order to achieve their goals (Leont'ev 1974: 22-23). Mediating artefacts might include physical and conceptual tools such as instruments, signs, language and machines, which are strategically selected to complete the task at hand.

Activities are not isolated systems; they occur as pragmatic moments, embedded in the contemporary world (Leont'ev 1974: 14-16). Activities might also be operationalized in ways that render them as common-sense ways or mundane acts, which fade into the background or become taken for granted (Nardi 1996: 37-38). Moreover, as objects change, so does the fundamental nature of the activity, however objects held in the minds of subjects are generally thought to remain somewhat stable prior to such substantial alterations so that they might be grappled with (Nardi 1996: 37-38).

Activity theory is commonly applied in knowledge, work and project management contexts, as well as in planning, design and digital curation. It is particularly useful in contexts wherein goals are clearly articulated, either as directed by a managerial position, or as otherwise agreed upon by well-aligned team members, who are assumed to be proficient in their well-defined and essential roles (Engeström 2000: 964). Activities may intersect and overlap across various domains of work in ways that contribute to regular decision-making strategies within complex organizations, and even to the emergence of innovative knowledge (Choo 2002; Engeström 2000: 972).

Situated Cognition

Situated cognition is a theoretical framework that examines the improvised, contingent and embodied experiences of human activity, or as Nardi (1996: 36) more aptly states, "the way activity grows out of the particularities of a given situation". It was formulated in response to a perceived over-reliance on cognitive approaches to supposedly rational problem solving, by raising consideration of the embodied and experienced situations in which actions are actually performed (Lave 1988; Suchman 1987). However it is still a rather behaviouristic approach that emphasizes responsiveness to the environment, while diminishing attention towards articulations or explanations posed by observed subjects. Explanations of activities are considered to be formulated post hoc, as justifications for acting a certain way in a given situation, rather than as signs of preemptive strategic planning (Nardi 1996: 40). Activities are observed closely from an outsider's perspective, and then narrated in such a way that ascribes meaning at least partially imposed by the observer.

It is common to see situated cognition approaches being used to describe everyday activities, as ordinary people navigate the worlds that they inhabit. It is also closely related to Lave & Wenger's (1991) theory of situated learning (also commonly referred to as a 'communities of practice' approach), whereby individuals acquire professional skills in relation to the social environments in which they are situated. Moreover, it has been used to evaluate strategic non-compliance with predefined protocols, or the unintended uses of objects and systems in ways that meet the needs of specific situation that have not necessarily been accounted for in their original design (cf. Garfinkel 1967; Suchman 1987; Suchman, Trigg & Blomberg 2002).

Distributed Cognition

Distributed cognition is a theoretical framework that highlights the synergistic relationships among people and things who operate within goal-oriented systems. Each component of a system is considered to contribute to a broader system-wide effort in some way, and only through their interlocking convergence can they accomplish something greater than the sum of their parts (Hutchins 1995). Generally, this approach assumes that all of a system's components are already in place and ready to be used. It is therefore oriented towards complete or closed systems, viewed with broad perspective (Nardi 1996: 42-43).

Distributed cognition is commonly applied to assess and troubleshoot human engagement with dynamic and complex machinery used in industrial or military settings. As an approach dealing with cognition in action, there is also emphasis on communicative aspects of action (Nardi 1996: 39); proponents have therefore developed useful methodological frameworks for documenting and analyzing conversations, combined gesture and speech, and the subtleties of professional communication and language (cf. Goodwin 1994; Hutchins 1995, 2010).

Framing an Adequate Comparison

In order to evaluate the suitability of activity theory, situated cognition and distributed cognition for providing a better understanding of socio-technical aspects of the archaeological process, the following concerns should be considered: how are the agency and relations pertaining to people and objects understood? How is the sociality of work accounted for, especially with regards to people's roles within project hierarchies, and the capability for people to learn and grow? How are meanings thought to be negotiated, communicated and modified over time, at personal and community levels of understanding? How might observations be conducted to examine work being done across different research environments, and as part of projects that are simultaneously unique and generalizable?

Case Study

These methodological approaches have been briefly applied to examine various related episodes of archaeological work conducted at an excavation of a prehistoric site in southern Europe. This project is considered to be representative of a broader class of archaeological research projects in various ways. Like many other archaeological projects, its research team composition and governance structure follows a common model – it comprises a director who coordinates the project, various specialists who are called in by the director to offer their expert input in the interpretation of finds, a series of trench supervisors who lead excavation and coordinate data

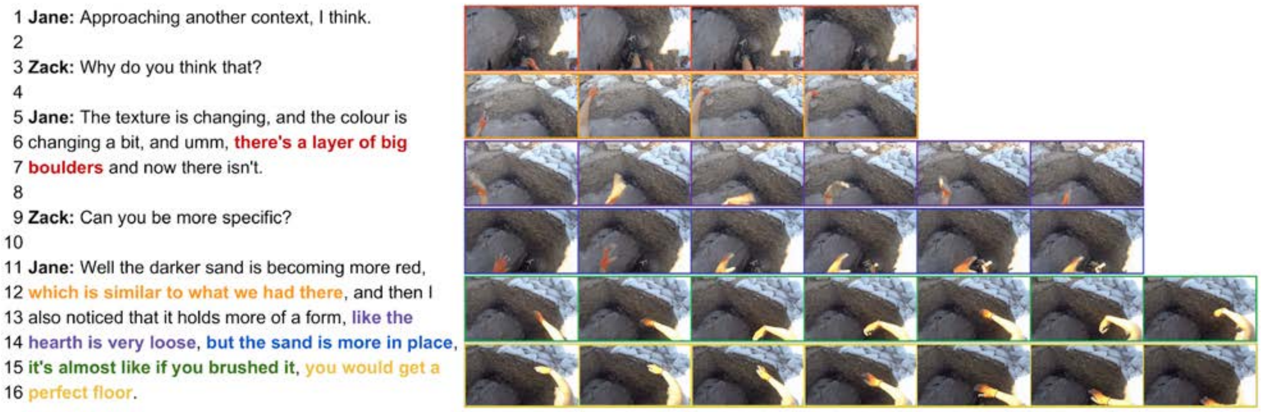

Figure 1. Explanation of a potential context change using gesture and speech.

collection, and excavators who are usually less experienced students who operate under the guidance of their assigned trench supervisors. It also relies extensively on archaeological surface surveys and assessments of the landscape to inform excavation strategies and guide interpretations of finds. Digital tools and methods are also being increasingly implemented, as informed by examples of their similar use elsewhere, and in a way that reinforces their subsequent adoption by others. Like any other archaeological project, it addresses common underlying research questions, and constantly compares its findings with similar work occurring in the vicinity. Moreover, it is reliant on and engaged with local communities, who support the research by agreeing to have their lands excavated, while also providing housing, food and other amenities to the mostly foreign research team.

This project thus serves as a salient case study that enables documentation of the pragmatic and multifaceted ways in which archaeologists reason and work their way through rather mundane activities that are commonly undertaken in similar research contexts. Due to the inherent power imbalances of academia, and of field-based research in particular, participants identities, as well as the identity of the archaeological project as a whole, have been anonymized in order to reduce potential risk to participants' professional reputations.

Methods

Multiple vectors of data collection were implemented. Archaeologists were recorded as they worked using GoPro action cameras, which were sometimes strapped to participants' heads so first person perspectives could be obtained. Detailed notes were also kept of observations in the trenches, at the dig house, in the museum, and throughout the season in various settings. Interviews were held with excavation staff, as well as with finds specialists, and the project's director, to better understand their situated perspectives regarding salient aspects of their work and regarding the ways in which they reason. These are more retrospective in nature, and differ from more casual field interviews, which tend to reflect thoughts on practices that were being undertaken at the moment. Lastly, documents produced and used by members of the project were examined, and are broadly defined to include recording sheets, reports, diagrams, finds bags, tags, scrap notes, descriptive monologues, stories and demonstrations. Specific attention has been paid to trace how ideas are transcribed and rendered across various kinds of media, and how this reflects the project's, and indeed the discipline's, dynamic information landscape.

All of this contributes towards the development of a large and integrated dataset that is then qualitatively analyzed in order to highlight the cognitive and communicative processes involved in the construction and curation of archaeological data. This entails coding segments of video, audio and text using language that serves to bridge the gap between the archaeological practices observed and the theoretical frameworks applied to explore them as epistemic activities and interfaces.

Episodes of Archaeological Practice

A series of related episodes have been selected from observations conducted during the summer of 2017. A brief overview of these episodes is provided before comparing how different methodological approaches may be applied to analyze them. All names presented here are pseudonyms.

The first episode is focused on a conversation between myself and Jane, a novice but also promising excavator. In this brief conversation, which occurred as I was observing her excavate a sondage, Jane explains how she identifies and differentiates a new context that she is coming down on.

One interesting aspect of this exchange is the series of gestures that she pairs with speech, which help convey what she means to say (Figure 1). She kicks the boulders as she refers to them, literally points out relations to previous experiences, and describes certain aspects of the soil by miming the ways that she would interact with them. Jane's combination of gestures and speech reveal the ways in which she semantically relates objects of interest to each other and to her own actions.

A similar conversation was observed between Jane and her trench supervisor, Basil, upon his return to the trench (Figure 2). Basil also happens to be the project's director, and often leaves Jane to work independently while he performs other tasks that are necessary to keep the project running smoothly.

To quickly summarize the entire exchange, Jane explains her interpretation of the soil to Basil, and after he evaluates Jane's account more closely, he provides her with instructions for how to proceed.

An interview held with Jane also provided insight regarding how she situates herself in relation to others, and how she understands her experiences as part of structured and rational system of knowledge (Figure 3).

Finally, handwritten observations were made of the practices involved in drawing trench sections at the very end of the season (Figure 4).

Observations were also made of section drawing at other trenches, though only the notes pertaining to the activities in Jane's trench are included here. Max is an extremely experienced excavator and is highly skilled at drawing sections. Carly is another skilled archaeologist who supervises a series of trenches nearby, but has no experience working in the area where Jane's trench is situated.

Analyzing Archaeological Practice

From an activity theoretic perspective, Jane's objectives as an excavator of a trench in this geo-archaeologically focused project are to identify and characterize the various sediments she encounters as she digs her way down to bedrock. She uses physical and conceptual tools in order to accomplish this task. Particularly notable is the geoarchaeological conceptual framework used to characterize and describe the site's various sediments, which was introduced to the project by Alf, who is a geoarchaeological specialist and the assistant field director, and whose ongoing dissertation work, in general terms, compares the geoarchaeology of this site to that of others in the region. The specialized conceptual framework is being implemented in order to systematically characterize the sediment according to professional geoarchaeological standards.

After observing Jane excavate the trench, various activities were delimited and modelled, in a similar manner as Engeström's (2000) application an activity theoretic approach to model various aspects of patient care in a children's hospital in Helsinki, Finland. This approach reduces archaeological practices into goal-directed activities, which are then evaluated as intersections of underlying aspects of work that become entangled when focusing attention upon a particular object. For example, the physical excavation of a context entails an excavator using various physical tools to move the material pertaining to the currently opened context out of the trench (Figure 5). Attention is focused on the currently opened context, with the goal of collecting all of the material in a discrete and tidy manner. A second act of identifying new sediments when they are encountered leverages physical and conceptual tools that help compare sediments within the trench and across the site (Figure 6). The division of labour establishes that trenches are the domains of their trench supervisors, and that it is the trench supervisors who are responsible for making decisive calls on how the stratigraphy is identified and organized. The use of a common geoarchaeological conceptual framework enables the supervisors to share a common point of view, however their conceptions and comparisons tend to be expressed using informal language and through indirect ref-

Jane : So, this is like still kind of a dark, dark brown, going into the sand, but it's like really tough, like hard to dig through, kind of. So I think maybe it's just context [?]. *((gesturing towards other side of the trench))* And then this is like really light grey, *((bobs hand up and down to emphasize these last three words))* and I thought it was just cuz it had just dried out, and I hadn't done this kind of [fill], but it's also really hard to dig, and like a really light grey, so I don't know if it's just remnants of this part, or what...

((Basil gets in the trench to take a closer look))

Jane: Or like maybe this is like, would it be possible that that's like an older hearth, like the other one that was leached out?

Basil: Yeah, hmm. So the colour here is the same as what you were digging, but the consistency has changed?

Jane: Yeah.

Basil: I would clean up, maybe just straighten that section a bit, [
[**Jane:** yeah
just to the depth that you started at for this context, [
[**Jane:** yeah
and then we'll clean up and carry on with... you know we can just write in the text that, you know, these are the differences, [
[**Jane:** yeah
but you know what, after we start to dig it it might change back to something much more familiar, [
[**Jane:** yea
and we can just say oh, it's like some kind of differential lens of material within it, [
[**Jane:** right
yea, or quite possibly a continuation of what we had before... [
[**Jane:** okay

Jane: Okay, so just clean up the walls, and then keep going, okay.

Basil: Yeah, but we can photograph, change numbers

Jane: Oh, okay.

Basil: We'll treat it as something different, you know we can write in the notes that there is a very good chance that it's still the same stuff, but the consistency changed [
[**Jane:** right
so, just to be careful.

Figure 2. A conversation between an excavator and her trench supervisor regarding a potential context change.

Zack: Can you tell me about challenges in comprehending something that you eventually learned, especially maybe at the beginning?

Jane: ... It's always hard to train your eye to see certain things, like sometimes Alfred would like take out a handful of sand and go like 'do you see the red flakes?' and I would be like 'no', or even like, pointing out stratigraphy, like see how this changes to this level, and it just kind of, **training your eye to see what they're seeing** is, sounds like an easy thing but it's actually hard to like, kind of, **pick out things that they want you to pick out**. And I think like now it's easier, like, 'oh, see how that's transitioning', or like, umm, even just like comparing peoples' trenches and like the contexts they're in, it's easier now but at the start it was like **'it looks the same to me'**, or like **'I don't spot what you're spotting'**, you know? And it's just a way of looking at things that I think that's the hardest part for me.

Zack: Do you know how that developed?

Jane: I think just like **repetitive, like every day, looking at stuff**, I think is like, just a good way of learning. I don't know if there's something specific but... and just hearing from like, **hearing Alfred pointing it out, hearing Basil pointing it out, hearing different supervisors pointing it out**, it was just different ways of explaining it or showing it to you that it starts to kind of, like, produce a form of knowledge.

Figure 3. Segment of an interview, wherein Jane explains how she learned to characterize sediments in a geoarchaeological manner.

erences. A third activity, the filling out of recording sheets, entails the formal description of excavated contexts in a more structured manner (Figure 7). Trench supervisors use formal language and standardized schema to describe the context in ways that facilitate comparison of contexts across the site; these schematic protocols are implemented as part of broader efforts to curate the data throughout the continuum of the project.

Others activity models might be derived for a wide array of related activities such as data entry into a digital database, the formulation of database queries, various aspects of finds processing and analysis, various actions involved in the physical storage and organization of finds, among other archaeological practices.

July 4th 2017
I will now observe Max and Carly draw the sections for trench 028. No one else is here, and Max expressed some confusion regarding what is going on in this trench. Moreover, Basil can not find the paperwork for 028, he is on top of the hill at either 033 or 034, and Jane is resting back at the dighouse. So it should be interesting to see how Max's drawing pans out with Basil's expectations.

Carly on the big boulder in the southeast corner. Max on the north side, with graph paper, taped down to his clipboard with bandaids. Carly calls out numbers to him as he marks them down. They called for my help for a moment because it was too deep for Carly. Upon hearing the elevation of the base at 1.5m along the edge, Max laughed and said it is was too deep, and that he would need another sheet of paper. This wind is going to make that horrendously difficult. So they reprioritized, and limited their scope to the upper part that would fit on the page.

July 5th 2017
Jane seems very comfortable in her trench, much more than Carly yesterday. Max is able to communicate with her, ask her questions. She also refers to her sediment description on her contexts sheets so that Max can annotate the textures more appropriately. He asked whether what they just did was the hearth and she said "no, it's the black-brown stuff above the hearth". He then wrote something like that down on his drawing. He also showed her the connected dots and asked her "does it look something like that?" and she answered that it does.

Figure 4. Observational notes regarding the practices involved in drawing trench sections.

This approach, based upon direct observation of work in action, dissects the various aspects of archaeological practices in order to understand how they are the product of a series of interacting entities and forces. It may be particularly useful for modelling common or mundane activities that are taken for granted due to their ubiquity. This might be applied to document 'recipes' for common archaeological practices (cf. Dallas 2015: 195), however such generalized formulae may not adequately account for their inconsistent implementation over time or across various local settings.

Situated cognition is an alternative approach that may be helpful for obtaining a realistic account of how skills are applied over time in the field, as excavators leverage their experiences to act on a given situation presented to them. For instance, as she incrementally excavates throughout the season, Jane develops a feel for the textures of the soils within her trench and in others where she has worked, which contributes towards her ability to characterize different kinds of sediments present across the site in a professionally acceptable manner. Jane recognized this herself during her retrospective interview, when she revealed that she initially found it difficult to "train her eye to see what they're seeing", and "they" seems to refer to more senior and specialized archaeologists, including Basil and Alf (Figure 3: lines 5-19). Jane also indicated that her continuous and active engagement with the sediments in the field, supported by the guidance of more established supervisors, contributed to her ability to do this work independently (Figure 3: lines 28-33). Additionally, her efforts to properly use controlled language and scales of measurement laid out in the geoarchaeological conceptual framework reflects such a commitment to aligning her view with that of others on the project, and within the broader disciplinary community as a whole.

Moreover, the ways in which Jane draws out conceptual entities based on her prior knowledge and experiences, and her presumptions regarding what is to be done with her observations, highlight how the object comes into view as part of a broader system of curated knowledge. This is a clear example of legitimate peripheral participation, or situated learning, whereby her gradual establishment as a member of the professional community will depend on her ability to be cognizant in a way that runs parallel with the community's standards, and she works her way from an outsider to an insider through continuous and practical engagement along the periphery of the archaeological community (cf. Darvill 2009; Goodwin 2010; Lave & Wenger 1991). This is well-illustrated in Jane's conversation with Basil, wherein she explained her interpretation of the soil while her

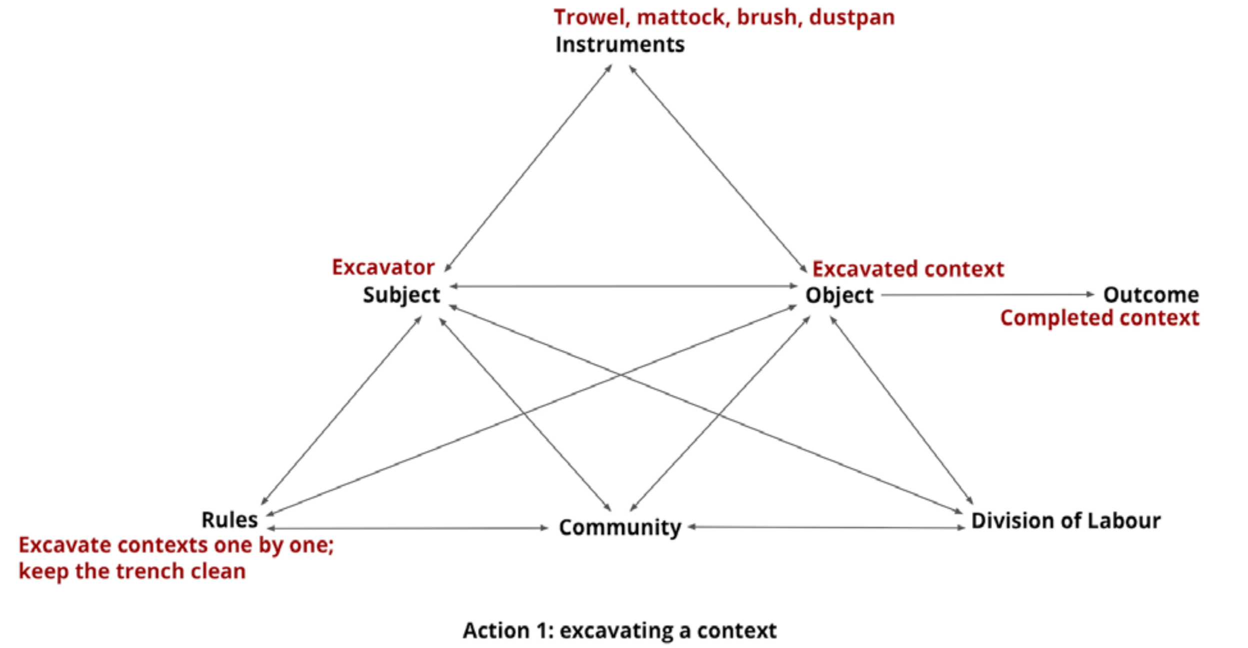

Figure 5. Activity model pertaining to the act of excavating a context

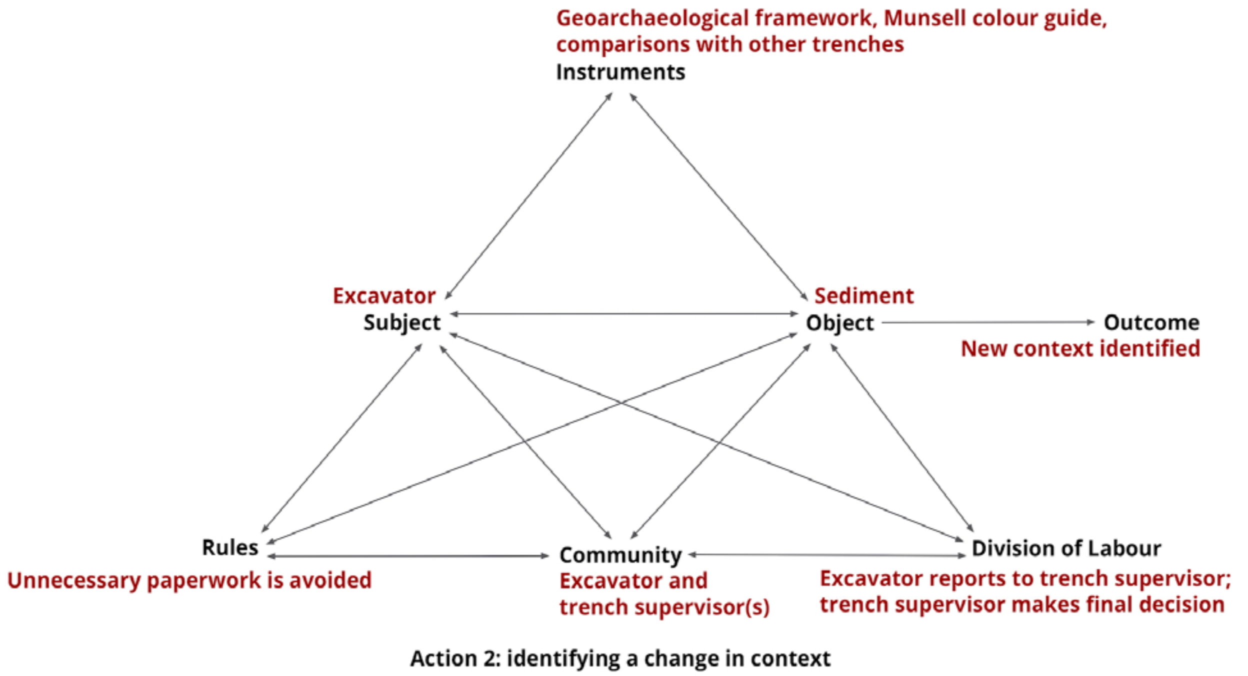

Figure 6. Activity model pertaining to the act of identifying a change in context.

supervisor responded with tentative agreement (Figure 2: lines 31-45, 54-59). Basil's subtle gestures that indicate where his tentativity lies, and Jane's respective acknowledgements served as signals that helped keep Jane's interpretations on track (Figure 2: lines 25-44).

Jane is thus involved in simultaneous and dialectic processes of upstreaming, whereby objects come into view as informed by what they should look like, and downstreaming, whereby objects are described and represented for further use down the line of the archaeological process (Dallas 2015: 190-191). As an active excavator in a specific and unique situation, Jane uses physical and conceptual tools to ensure that what she interprets is true to the things she ob-

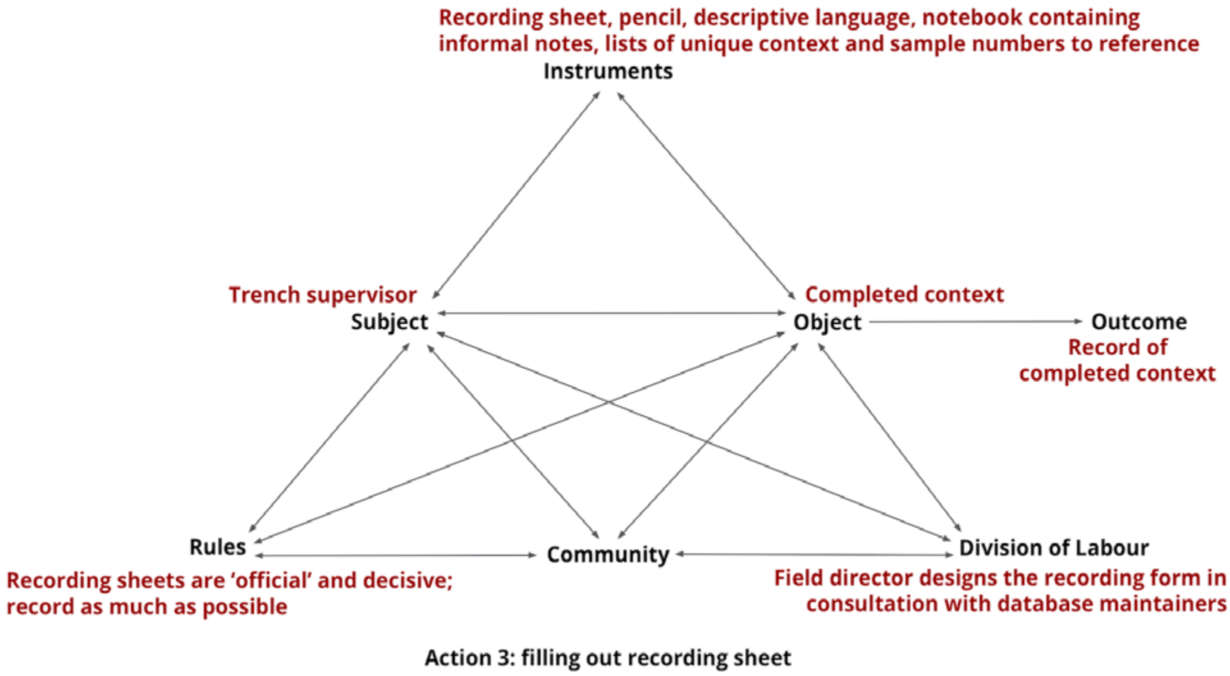

Figure 7. Activity model pertaining to the act of filling out a context recording sheet.

serves, and also imposes order upon these objects so that her direct observations might be communicated and used in secondary research environments.

Jane's work is therefore framed as experienced, embodied and responsive to local circumstances as beheld by her unique perspective. However, as Goodwin (2010) highlighted in his examination of archaeological learning in the field, certain tools such as the Munsell colour chart, help individuals translate their own unique experiences to a series of communal references points. This example of professional training, where students are taught how to see what their supervisors are seeing, can be conceptualized in terms of a situated learning experience, similarly to the earlier examination of the conversation between Jane and Basil. However, this scene can also be examined using a distributed cognition framework, which highlights the intersections among human and non-human agents, which are integrated to form stable communicative links. In other words, distributed cognition may be applied to examine how human and non-human agents are mobilized as parts of coordinated efforts to produce knowledge that could not have been derived from any single individual working in isolation.

Archaeological projects may thus be conceptualized as assemblages of people, things and ideas used to support individual efforts as well as the mutual goals of the project as a whole. Distributed cognition is therefore useful for examining the coordination of archaeological practices that make up broader systems of work. This requires the observer to consider aspects of archaeological practices that extend beyond the here-and-now, such as projections, transcriptions, imaginations or hypotheses of potential outcomes that tie in with further work being done over time. In this sense, archaeological practices may be examined as contributions to carefully planned methodological protocols or research programs, wherein communication of ideas and observations is key to their successful implementation.

Section drawings constitute good examples of this. Section drawing essentially entails transposing various points that outline an excavated context, which are observed on the vertical face of the trench, onto a sheet of paper, aided by the use of grid systems that serve to maintain the proportional distance between plotted points. The result is a proportionally-intact representation of the polygons observed on the trench's vertical surface. In practice, this is accomplished by assembling a communication system comprising a series of physical and

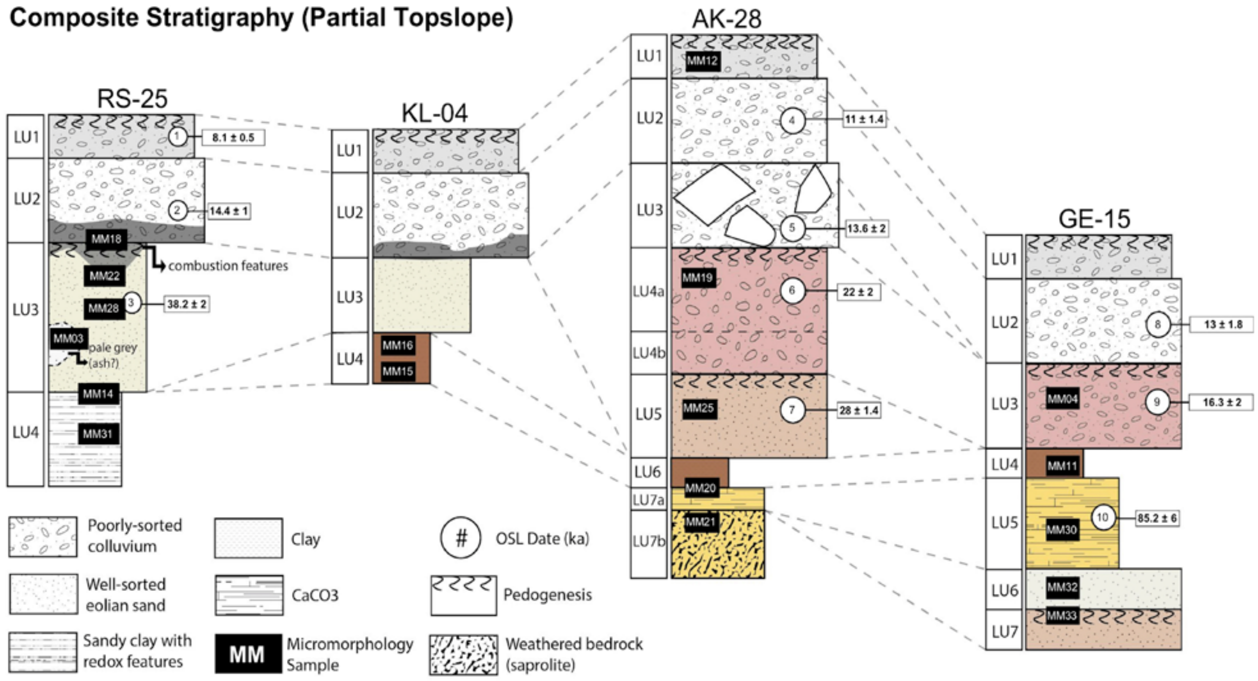

Figure 8. Replica of a document that synthesizes data collected using various kinds of methods and across various segments of the project.

conceptual tools – such as string, plumbobs, pencils, notches marked along a tape measure, graph paper and other ad hoc implements – so that a stable transcription of the trench can be transported back to the dig house where it stands in as a record of the trench itself.Although the tangle of tools that are used to construct the representation is unstable and susceptible to disturbance, it includes a fixed reference point that ensures that the plotted information is spatially grounded. The locations from which dating samples were taken, which have been shot in using a total station, are thus plotted in accordingly afterwards. Moreover, the geoarchaeological characteristics of each context are encoded for each polygon. The relative depths and age ranges pertaining to dating samples from various trenches are combined with an integrated representation of the geoarchaeology of the site as a whole in order to determine the relative ages of unsampled trenches and to plan for further excavation and sampling based upon such syntheses (Figure 8).

It thus becomes apparent how Jane's efforts to delimit discrete contexts and adopt a geoarchaeological conceptual framework as she does so are brought to bear upon broader workflows. In this specific case, the hierarchical nature of the project's organizational structure enables people's work to be orchestrated according to carefully planned research protocols designed by the project's director.

Conclusion

Systematic inquiries regarding the practical implementation of archaeological practices can provide lots of insight regarding the underlying epistemic commitments underpinning common research activities. However, it is important to be self-aware and purposeful when conducting such meta-disciplinary reviews. Different methodological outlooks require the use of different kinds of data, and may identify different loci of agency, account for social contexts in different ways, and exhibit varying capabilities to examine continuity of archaeological practices over time and across localized circumstances.

The methodological frameworks discussed here have been critically evaluated over the past several decades in efforts to better understand the impacts and implications of their use to examine work – and scholarly research practices in particular – in action (Haraway 1988; Law 2004; Nardi 1996; Pickering 1992b). This paper is meant as a brief primer of three such approaches, including a comparison of how they might be implemented to critically examine archaeological practices as processes of meaning-making. A more in depth review of that literature is advised to gain a greater understanding of each methodological framework's epistemic sensitivities and limitations, prior to initiating grounded research regarding the enaction of archaeological practices.

Such work is important moving forward due to the epistemic challenges that lie ahead as open scholarship increasingly enables archaeological authority to be questioned and practical expertise to be trivialized (cf. Morgan and Pallascio 2015; Ratto 2012; Richardson & Lindgren 2017). The heterogeneity of scholarly practice and of the different kinds of data that inform various scholarly communities in different ways is important to highlight in a professional context that favours highly technical, reductive and immutable conceptions of what archaeology and archaeological data is and should be. This is particularly important with regards to contemporary pressures to share the products of archaeological research, namely research data, openly and publicly, which exhibits genuine virtues but that also warrants critical reflection regarding the ways in which archaeological data is presented and framed. Archaeological practices and the products of archaeological research exhibit unique idiosyncrasies that may not be adequately accounted for under the curatorial frameworks that currently exist. If we are to consider data sharing as an integral part of archaeological research, it must extend from contemporary practices and relate to practical needs (Huggett 2012; Huvila 2018). Therefore, archaeological research, in all its stages and forms, needs to be considered as part of a continuous and richly textured curatorial process involving various tools, concepts, experiences and communication strategies, which can be reflected upon in various ways (Dallas 2015; Dallas 2016; Huggett 2015).

References

Choo, C W 2002 Sensemaking, Knowledge Creation, and Decision Making. In: Choo, C W and Bontis, N. (eds.) *The Strategic Management of Intellectual Capital and Organizational Knowledge*. pp. 79–88.

Dallas, C 2015 Curating Archaeological Knowledge in the Digital Continuum: from Practice to Infrastructure, *Open Archaeology*, 1(1): 176–207. DOI: https://doi.org/10.1515/opar-2015-0011

Dallas, C 2016 Digital curation beyond the "wild frontier": a pragmatic approach, *Archival Science*, 16(4): 421–457. DOI: https://doi.org/10.1007/s10502-015-9252-6

Darvill, T 2009 Linking fieldwork, theory and knowledge in teaching prehistoric archaeology, *Research in Archaeological Education Journal*, 1(2): 5–20.

Engeström, Y 2000 Activity theory as a framework for analyzing and redesigning work, *Ergonomics*, 43(7): 960–974. DOI: https://doi.org/10.1080/001401300409143

Garfinkel, H 1967 *Studies in Ethnomethodology*. Englewood Cliffs: Prentice Hall.

Goodwin, C 1994 *Professional Vision, American Anthropologist*, 96(3): 606–633. DOI: https://doi.org/10.1525/aa.1994.96.3.02a00100

Goodwin, C 2010 Things and their embodied environments. In: Malafouris, L and Renfrew, C (eds) *The cognitive life of things: Recasting the boundaries of the mind*. Cambridge: McDonald Institute of Archaeological Research. pp. 103–120.

Haraway, D 1988 Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective, *Feminist Studies*, 14(3): 575–599. DOI: https://doi.org/10.2307/3178066

Huggett, J 2012 Lost in information? Ways of knowing and modes of representation in e-archaeology, *World Archaeology*, 44(4): 538–552. DOI: https://doi.org/10.1080/00438243.2012.736274

Huggett, J 2015 A manifesto for an introspective digital archaeology, *Open Archaeology*, 1(1): 86–95. DOI: https://doi.org/10.1515/opar-2015-0002

Hutchins, E 1995 How a Cockpit Remembers Its Speeds, *Cognitive Science*, 19(3): 265–288. DOI: https://doi.org/10.1207/s15516709cog1903_1

Hutchins, E 2010 Imagining the Cognitive Life of Things. In: Malafouris, L and Renfrew, C (eds) *The cognitive life of things: Recasting the boundaries of the mind*. Cambridge: McDonald Institute of Archaeological Research. pp. 91–102.

Huvila, I 2018 Knowledge production with data from archaeological excavations. In: Huvila, I. (ed.) *Archaeology and Archaeological Information in the Digital Society*. London: Routledge. pp. 53–69. DOI: https://doi.org/10.4324/9781315225272-11

Knorr Cetina, K 1999 *Epistemic Cultures: How the Sciences Make Knowledge*. Harvard University Press.

Lave, J 1988 *Cognition in practice: Mind, mathematics and culture in everyday life*. Cambridge University Press.

Lave, J and Wenger, E 1991 *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.

Law, J 2004 *After Method: Mess in Social Science Research*. Psychology Press.

Leont'ev, A N 1974 The Problem of Activity in Psychology, *Soviet Psychology*, 13(2): 4–33. DOI: https://doi.org/10.2753/RPO1061-040513024

Lucas, G 2012 *Understanding the Archaeological Record*. Cambridge University Press.

Morgan, C and Pallascio, P M 2015 Digital Media, Participatory Culture, and Difficult Heritage: Online Remediation and the Trans-Atlantic Slave Trade, *Journal of African Diaspora Archaeology and Heritage*, 4(3): 260–278. DOI: https://doi.org/10.1080/21619441.2015.1124594

Nardi, B A 1996 Studying context: A comparison of activity theory, situated action models, and distributed cognition. In: Nardi, B A (ed) *Context and consciousness: Activity theory and human-computer interaction.* The MIT Press. pp. 69–102.

Pickering, A 1992a From Science as Knowledge to Science as Practice. In: Pickering, A (ed.) *Science as Practice and Culture.* University of Chicago Press. pp. 1–26.

Pickering, A 1992b *Science as Practice and Culture.* University of Chicago Press.

Ratto, M 2012 CSE as epistemic technologies: Computer modeling and disciplinary difference in the humanities, Leng, J and Sharrock, W (eds.) *Handbook of Research on Computational Science and Engineering: Theory and Practice*, 567–586. DOI: https://doi.org/10.4018/978-1-61350-116-0.ch023

Richardson, L-J and Lindgren, S 2017 Online Tribes and Digital Authority: What Can Social Theory Bring to Digital Archaeology? *Open Archaeology*, 3(1): 139–148. DOI: https://doi.org/10.1515/opar-2017-0008

Suchman, L A 1987 *Plans and situated actions: the problem of human-machine communication.* Cambridge: Cambridge University Press.

Suchman, L, Trigg, R and Blomberg, J 2002 Working artefacts: ethnomethods of the prototype, *The British Journal of Sociology*, 53(2): 163–179. DOI: https://doi.org/10.1080/00071310220133287

Wylie, A 2017 How Archaeological Evidence Bites Back: Strategies for Putting Old Data to Work in New Ways, Science, *Technology, & Human Values*, 42(2): 203–225. DOI: https://doi.org/10.1177/0162243916671200

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