Undine Lieberwirth

3D GIS Voxel-Based Model Building in Archaeology

Abstract: The development of three-dimensional representations of archaeological stratigraphical units and the representation of relationships between them was described as an "illusive goal" twelve years ago (Harris/ Lock 1996). This paper takes this statement as a challenge. It describes the current technical standard of OSS GIS (Open Source Software Geographic Information Systems) which are able to create volumetric, geo-referenced models of archaeological stratigraphy. In addition, the paper demonstrates the enhanced potential for archaeological post-excavation analysis of the new software prototype in comparison to 2D GIS analysis functionality. The applied OSS offers not only free access to the software itself but also provides the basis for further software improvements, which strive towards addressing archaeological questions directly via GIS.

Introduction

Archaeological deposits have been recorded in 3D space as paper drawings and increasingly as digital maps, via the use of total station. In both cases, deposits and artefacts are represented by adjusted 3D (x, y and z) co-ordinates. With this data at hand, archaeologists have tried to create 3D models of previously destroyed deposits in order to gain a better understanding of the natural and cultural remains.

The aim of this study was to create a three-dimensional virtual model of archaeological stratigraphy as a basis for further analysis within a GIS. To satisfy these requirements, an attempt was made to create an abstract model on a quantified basis. In contrast to former approaches, the software was developed under an Open Source licence in order to provide a useful tool freely available for further applications and research.

In order to reconstruct past human societies, we first need to understand their remains. These not only include artefacts and architecture but also deposits, which can be described as compact masses of organic and inorganic material. These deposits have been treated with more care ever since archaeologists such as Schliemann and Petrie recognized their importance at the end of the 19th century. However, the need to understand archaeological stratigraphy and its content thoroughly, as well as the arrangement and relationships of objects within these deposits, led to the conclusion that a quantified representation could maintain an objective point of view and provide the user with further options for spatial analysis.

The process of model building – creating a model of the real world – helps to summarise information as well as to find groups within the data. Since this data is becoming more and more complex due to increasingly advanced excavation methods, advanced spatial analysis methods could also help to sort and handle the large quantity of information being produced.

Archaeological deposits are solid three-dimensional objects, and should be modelled as such. Since most Geographic Information Systems can only handle draped (2.5D) models at present, the challenge of this study was to represent archaeological data as 3D volumes in a geo-referenced space.

Research History and Research Aims

Several attempts have already been made to meet these requirements by creating models of three-dimensional archaeological stratigraphy. These attempts can be classified into two groups based on the tools which were used. One group used commercial software, generally developed for addressing geological questions (Reilly 1992; Harris / Lock 1996; Nigro 1999; Barceló / Vicente 2004; Cattani / Fiorini / Rondelli 2004; Bezzi et al. 2006). The other group developed its own software to address archaeological questions specifically (Green 2003; Zabulis / Patterson / Daniilidis 2005; Kochnev / Zdanovich / Punegov 2004). A detailed description is given elsewhere (Lieberwirth 2007). However, neither group has produced a commonly applicable tool for archaeology. One reason for the failure of the first group is that archaeological institutes, companies or heritage management services can rarely afford commercial software. The same is true for the bespoke software, which is not available to the general community because of licence restrictions or similar reasons.

Considering the hard work which has been done in order to create bespoke software, it is particularly unfortunate that it has not spread further. Hence, one main research aim of this study became the application of OSS, since it makes software affordable, gives insight into the program's source code and, moreover, gives access to the algorithms employed. Furthermore, OSS is able to compete with commercial software as long as it is maintained by a large user community. A second objective was to access GIS's full potential for querying, spatial analysis, statistics etc. Thirdly, the project aimed to be able to calculate the volume of the 3D objects that the system would portray.

The Case Study

Theoretical Considerations

According to the requirements outlined above, an OSS package needed to be found. GRASS GIS, an Open Source GIS Software package, was chosen for this case study because it fully supports the voxel ("volume pixel") data model appropriate for the task. GRASS is able to interpolate values (w-attributes) attached to vector points within 3D space. This attribute value needs to be a floating-point number (a measured value). The result is a solid object consisting of voxels each carrying an interpolated attribute value (similar to the elevation value in 2D GIS). In order to create this output the data had to be prepared in the manner described below.

Data Preparation

As mentioned above, the commonly used GRASS GIS 3D interpolation module r.vol.rst requires x-, y- and z-vector points with a floating point value attribute.

The first step of data preparation was therefore to convert the paper drawings *(Fig. 1)* into a digital format. This was done using a digitizer tablet and the CAD software AutoDesk Map 2004. The whole excavation area consisted of twelve trenches, which were all treated in the same way. Most of these were documented with only one cross-section drawing. The digital cross-section version was therefore copied and moved within the virtual 3D space, a user-defined co-ordinate system (UDS) within CAD, to the opposite trench's side to produce a three-dimensional record *(Fig. 2)*. Elevation values of the trenches were obtained from values recorded on the plan drawings.

In the next step, the cross-sections were connected by straight lines marking the upper or lower surface of a deposit (*Fig. 2*, arrows). The start and end points of these perpendicular lines connect the profiles to places of interest, i.e. places where the unit surfaces' courses vary rapidly. These lines can be called contour-lines because they also contain elevation values.

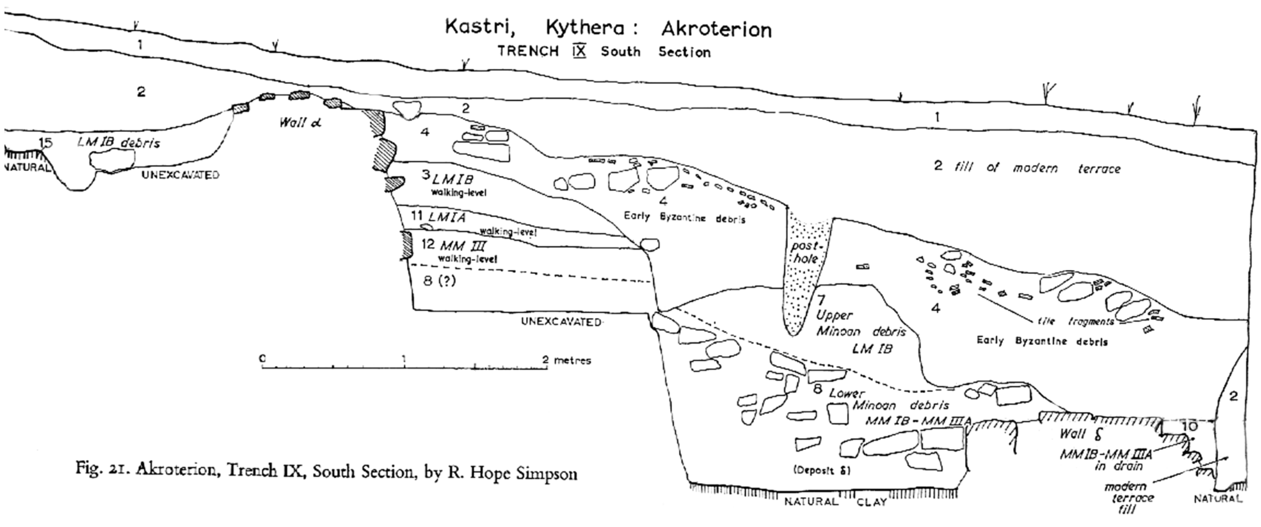

Fig. 1. Paper drawing, trench IX, south section, Akroterion Kythera.

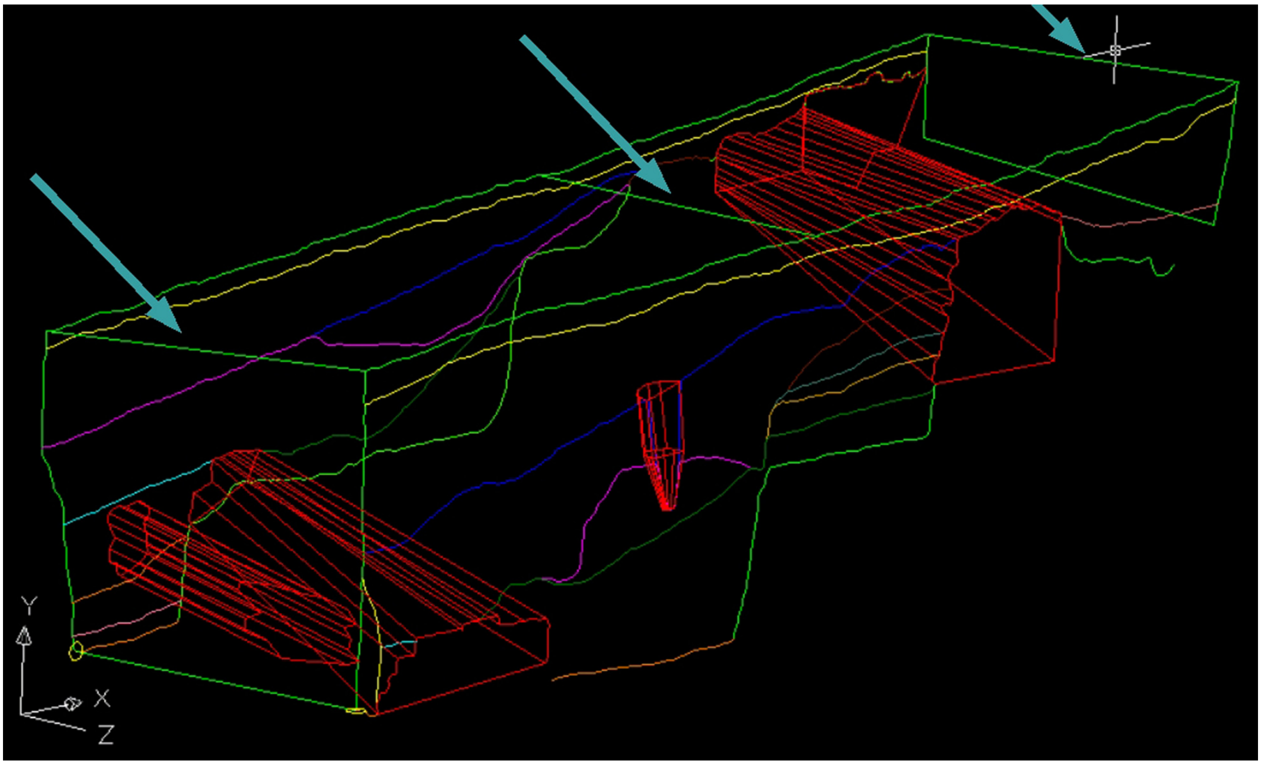

Fig. 2. Trench IX in 3D space with connection lines of each unit surface, Akroterion Kythera, generated in AutoDeskMap 2004.

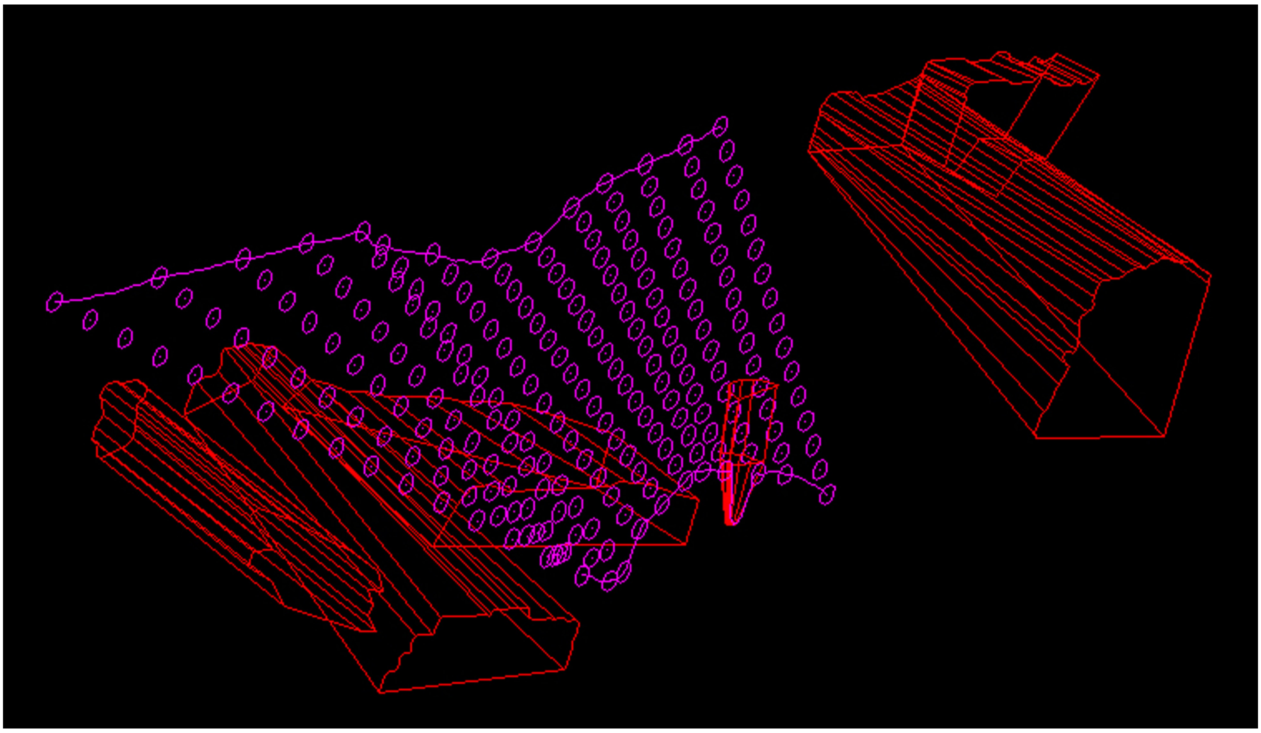

Fig. 3. Trench XII in 3D space with broken connection lines (vector points) of unit surface 7, Akroterion Kythera, generated in AutoDeskMap 2004.

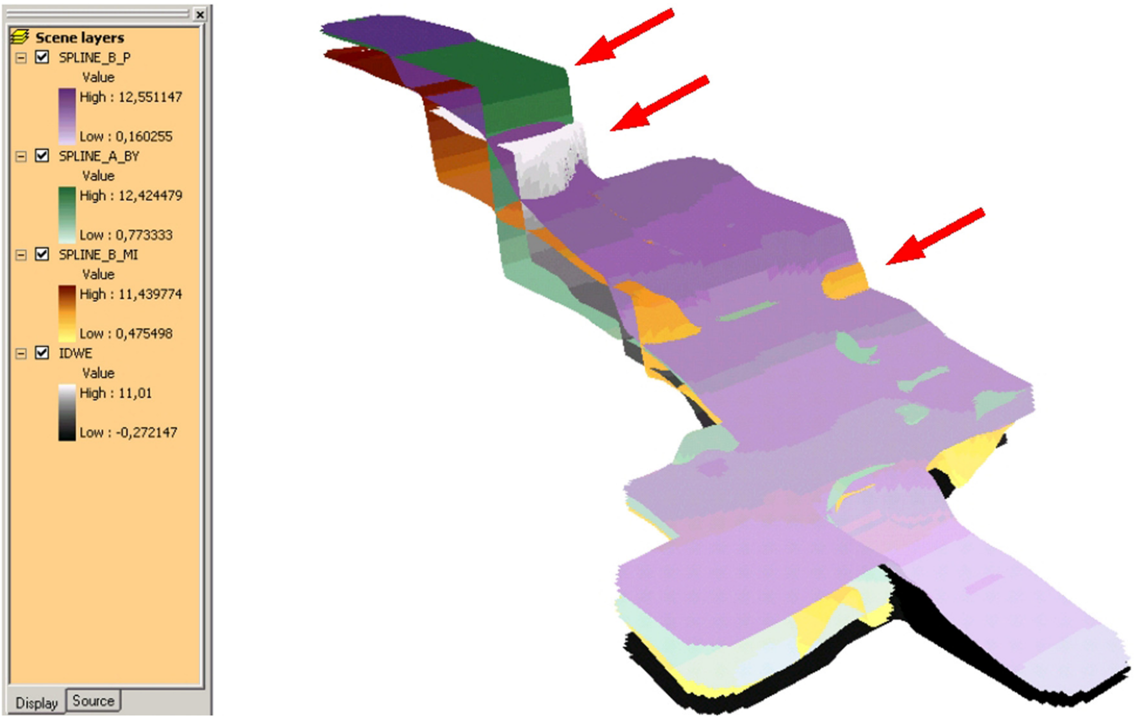

Fig. 4. 2.5D depiction of DEMs of the entire excavation representing four periods, arrows indicate places of overlapping, trench I-XII, Akroterion Kythera, generated in ArcScene.

The third step was to break the contour-lines into points. Using this method it was possible to create vector point "carpets" for each trench and each unit surface *(Fig. 3)*. The vector points created in this way provided the basis for the creation of a voxel model in GRASS GIS, as they formed the basis for the individual raster Digital Elevation Models (DEMs) *(Fig. 5)*.

Strategy I

Such DEMs were prepared for each unit surface of all trenches for four main periods. They were finally combined in order to get digital elevation models for the entire excavation *(Fig.* 4*)*. However, the final combination of the four digital elevation surfaces showed places of overlap (*Fig.* 4, arrows). The reasons for this were great information gaps between the excavation trenches and the extreme variation due to the sloping location. Hence, this strategy had to be discarded.

Strategy II

Following the outcome of strategy I, in a second attempt only one trench was chosen to demonstrate this new analysis technique. Dealing with only a single trench, without great information gaps, was intended to exclude the source of error. The data was prepared as above. Verification in 2.5D (*Fig.* 5), by combining all digital unit surfaces of the chosen trench IX, now showed a successful result according to the law of stratigraphical succession (Harris 1989, 29), stating that unit surfaces of different time periods cannot overlap.

The data was now prepared and ready for use in GRASS GIS. A problem was the w-attribute which was required by the GRASS interpolation module. Since it had to be a measured value which could not yet be provided by the legacy data, the interpolation routine had to be modified in an interdisciplinary co-operation which led to the development of the new GRASS GIS module *r.vol.dem*. Its underlying idea for expressing archaeological stratigraphy in a quantified way is to interpolate the layers' label numbers (categories), which indicate the stratigraphical classification.

The new module *r.vol.dem* is able to calculate "voxel maps" between at least two DEMs. The already prepared trench IX DEMs *(Fig. 5)* provided the basis for further calculations. The algorithm, used by *r.vol.dem,* is a so-called "flood-filling" algorithm (Lieberwirth 2007). It fills 3D space between two DEMs with categorized voxels *(Fig. 6)*. The input

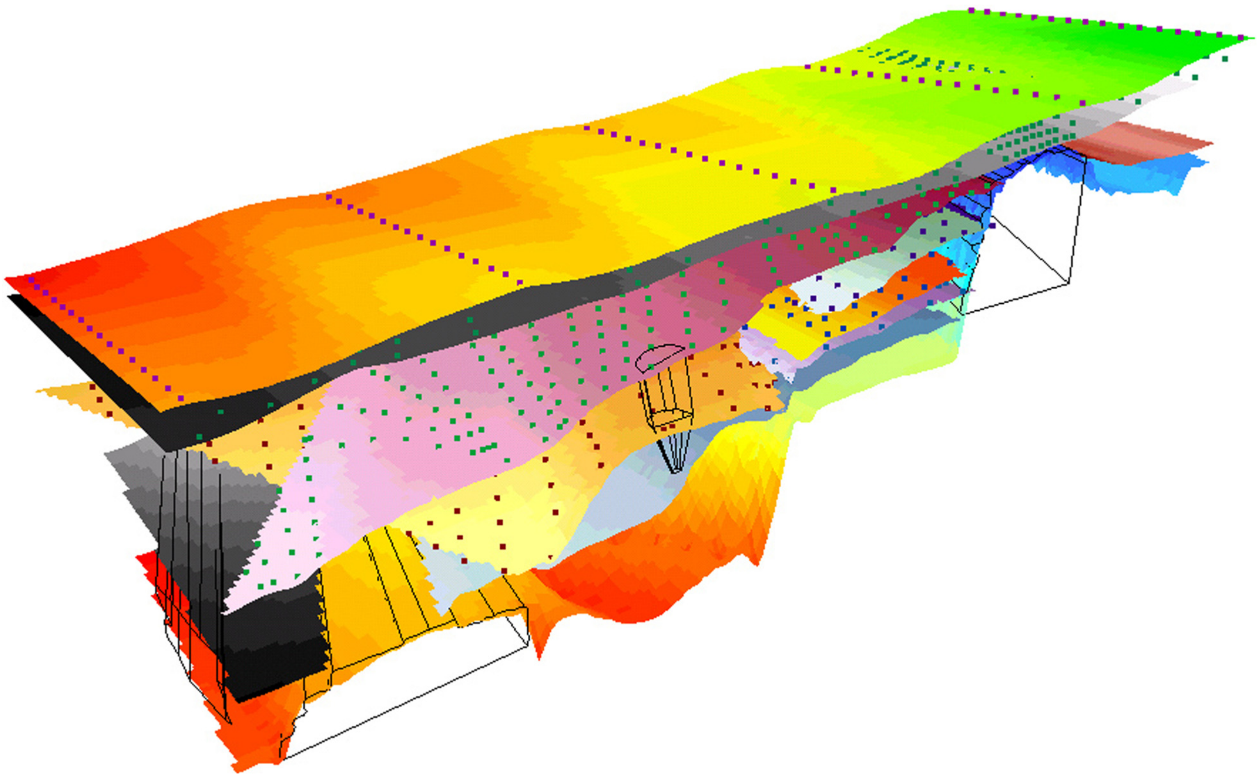

Fig. 5. DEMs of all unit surfaces and polygons of the features (architecture and posthole) of trench IX, Akroterion Kythera, generated in ArcScene.

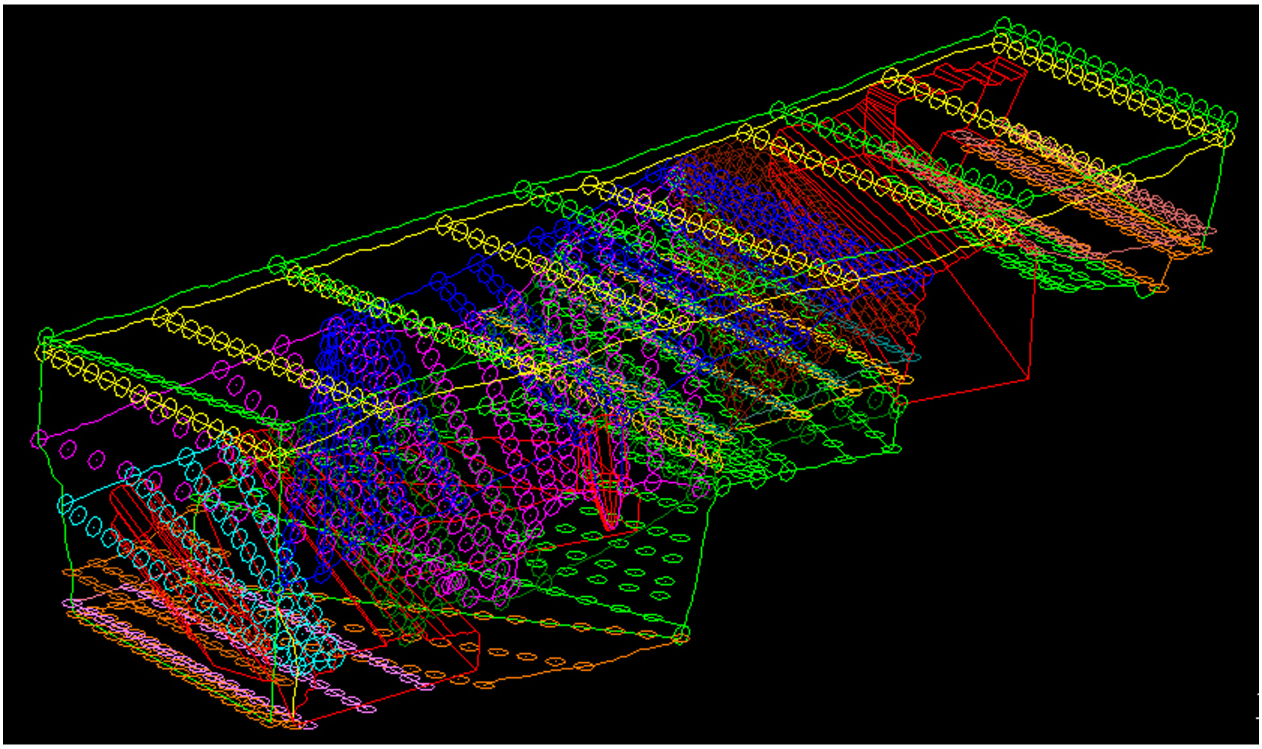

Fig. 6. Voxel-based model of unit 7 and 8, trench IX, Akroterion Kythera, generated by GRASS GIS r.vol.dem, visualised in ParaView.

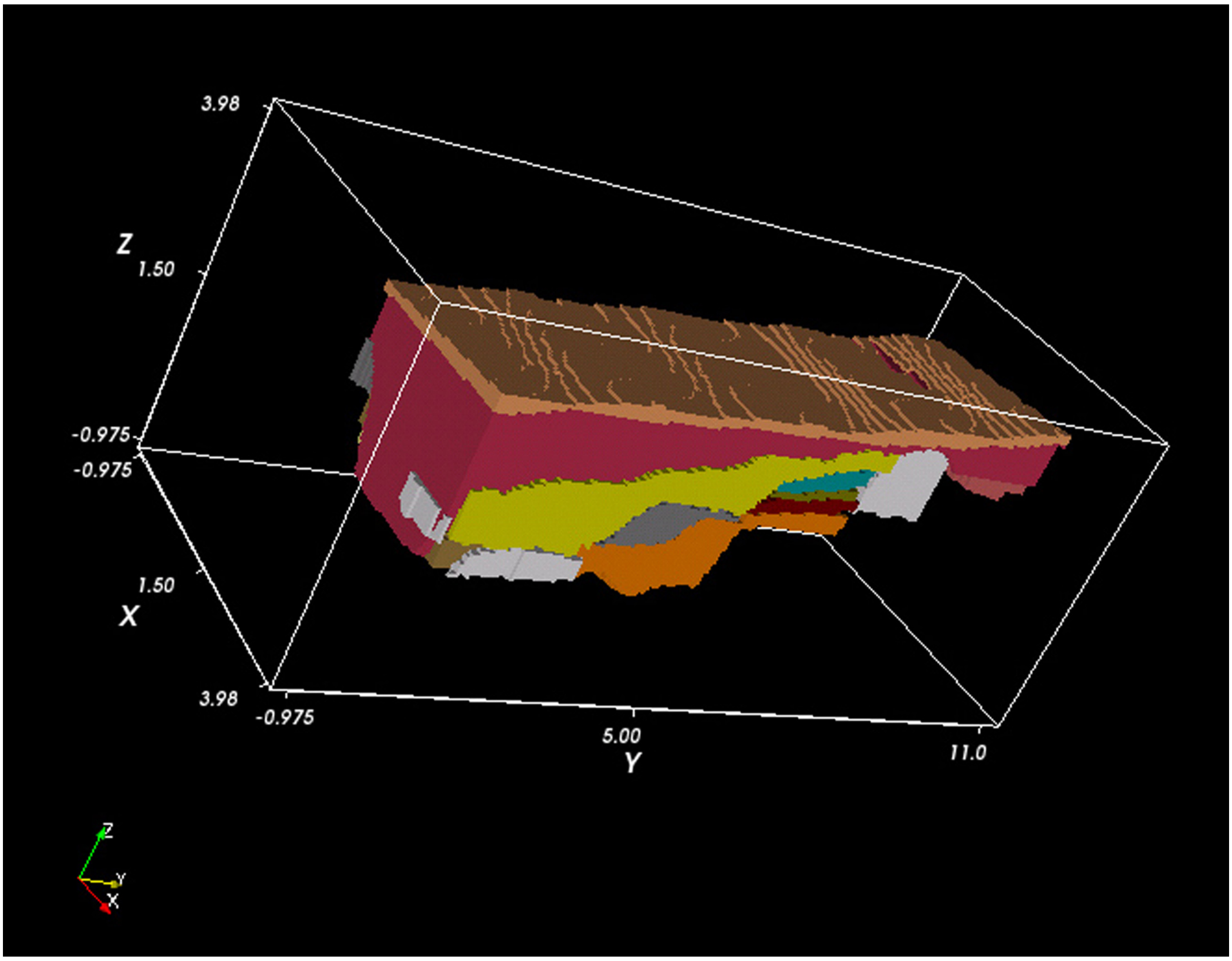

Fig. 7. 3D voxel-based depiction of all trench IX units, Akroterion, Kythera, generated in GRASS GIS and visualised in ParaView.

bottom and top DEMs represent the bottom and top boundaries for the "voxeled" stratigraphical unit, in this case the implicit structure. The voxels represent only a single category value for each stratum, and therefore received a single colour, each according to the label numbers *(Figs. 6, 7)*. This algorithm is therefore more suitable for dealing with the special nature of interpreted archaeological stratigraphy. Since measured representations of stratigraphy are very rare in archaeological stratigraphy, the simple "flood-filling" algorithm can be considered the most suitable for this case study. However, future applications should consider including measurable properties such as soil colour or soil precipitation in order to generate a realistic 3D interpolation.

As a first approach, simplified simulated data was used which represented only two unit surfaces, a top and a bottom surface, of one stratigraphic unit *(Fig. 6)*. Before running the *r.vol.dem* module, one needs to adjust the three-dimensional extent of the 3D interpolation window which works as an analytical mask in the GRASS GIS module *g.region*. This procedure also adjusts the voxel's size, which defines the 3D resolution of the entire stratum (like the pixel resolution does in 2D GIS). Furthermore, it is possible to adjust the height and width of the voxels independently in order to obtain a cube or cuboid voxel shape. In general, the smaller the voxel's size, the higher the resolution, and the more accurate the 3D representation.

The simulated results of strategy II were satisfying. Hence, the way was now clear for applying the module to real data of trench IX. The eventual calculation of all trench IX units of the Kythera legacy data was done using the GRASS GIS module *r.vol.dem*, and the result visualised by ParaView *(Fig. 7)*, another OS program specializing in 3D data visualisation and exploration.

Analysis

The OSS ParaView is not only a visualisation program; it also offers additional options for analysis. One is the possibility to make vertical and horizontal cross-sections at any location and in any direction. The trench can be studied from all sides with its entire classified stratigraphy inside a geo-referenced bounding box. Each single layer can be cut vertically to gain an insight into the trench's interior structure. Furthermore, it is possible to add vector points, to show, for example, artefact positions and, by adjusting transparency, to optically retrieve them within each layer. The points can also be retrieved by ID-numbers. One can also turn each voxel object on and off separately. ParaView also offers the option of measuring the distance between any two points in the 3D space. Finally, it is possible to visualise each layer separately and combine them to "recreate" the entire trench as a virtual 3D model in a geo-referenced space (Lieberwirth 2007).

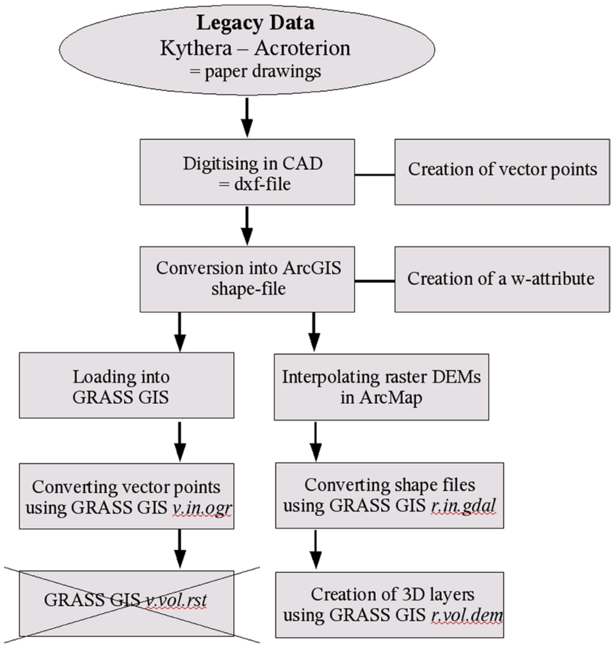

Fig. 8. Process of work.

Summary

Most famous archaeological sites have probably already been excavated and documented. Therefore, archaeologists are often confronted with old excavation records, documented on paper. The legacy data available for this study was paper drawings from the documentation of excavations carried out in the 1960s (Coldstream / Huxley 1972) with plan drawings and cross-sections. Due to the lack of information, this study focused only on archaeological stratigraphy and can hence be called non-artefactual. However, as this case study shows, this kind of documentation is still of vital use for further analysis even with new technology. It is an example of how one could deal with old excavation records within a GIS.

The result is now not only a 3D GIS, it also includes a time sequence: the fourth dimension. So the final outcome is a 4D GIS, and I would like to suggest calling it multidimensional "Archaeological Information Modules" of a GIS. The focus can now shift to certain diachronic and synchronous parameters inside archaeological stratigraphy.

The entire process virtually brings alive the physically destroyed archaeological site in three-dimensions and allows re-excavation, step by step, disregarding the excavation method, following the natural course of the soil types (single context record) or digging in artificial layers. One can also explore the taphonomic and site formation processes of archaeological stratigraphy. Thirdly, we can not only visualise stratigraphy, as was the original intention, but also structures like architecture, pits and postholes and can furthermore calculate their volume. A fourth advantage is that one can draw conclusions about the relationships between stratigraphy and artefacts in 3D space.

The model shows more than mere "pretty pictures". Any user has access to the meta-data, the legacy data, the program and the algorithm; further options include volume calculation and multidimensional representations.

Finally, one can conclude that additional information is provided by the 3D approach. When applying the last strategy *(Fig. 8)*, it became possible to fulfil the research aims of using an OS GIS for creating quantified archaeological stratigraphy with 3D information. However, only one of the first steps has been done towards utilizing the full potential of GIS. Spatial GIS analysis functions are not yet applicable in a 3D GIS. Hence, a further improvement might include – for example – 3D statistics.

The attempt to create a voxel-based, three dimensional model of archaeological stratigraphy even out of old excavation data has turned out to be a success. This case study shows that this kind of documentation is still of vital use for further analysis, even with new technology in place. It is an example of how one could deal with old excavation records within a GIS. The process described in section 3.2. is admittedly rather questionable, since a large number of assumptions were made. Since a model is always only as precise as its legacy data (Green 2003), in this case the imprecision of the model is evident but comprehensible. The first considerations of digital model building out of old excavation data should be the scale factor and question of what kind of further analysis the model will be used for.

References

Barceló / Vincente 2004

J. A. Barceló / O. Vicente, Some Problems of Archaeological Excavation 3D Modelling. In: K. Ausserer Fischer / W. Börner / M. Goriany / L. Karlhuber-Vöckl (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. BAR International Series 1227 (Oxford 2004) 400–404.

Bezzi et al. 2006

A. Bezzi / L. Bezzi / D. Francisci / R. Gietl, The Application of Voxel in Archaeology. Settimo Meeting Degliutenti Italiani di GRASS, Genova, Italy, febrarrio 2006. http://www.arc-team.com [10 Jun 2006].

Cattani / Fiorini / Rondelli 2004

M. Cattani / A. Fiorini / B. Rondelli, Computer Applications for a Reconstruction of Archaeological Stratigraphy as a Predictive Model in Urban and Territorial Contexts. In: K. Ausserer Fischer / W. Börner / M. Goriany / L. Karlhuber-Vöckl (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. BAR International Series 1227 (Oxford 2004) 299–303.

Coldstream / Huxley 1972

J. N. Coldstream / G. L. Huxley (eds.), Kythera: Excavations and Studies (London 1972).

Green 2003

D. A. Green, Stratigraphic Visualisation for Archaeological Investigation. PHD Dissertation (London 2003).

Harris 1989

E. C. Harris, Principles of Archaeological Stratigraphy (London 1989).

Harris / Lock 1996

T. M. Harris / G. R. Lock, Multidimensional GIS: Exploratory Data Approaches to Spatial and Temporal Relationships Within Archaeological Stratigraphy. Analecta Praehistorica Leidensia 28, 1996, 307–316.

Kochnev / Zdanovich / Punegov 2004

V. Kochnev / G. Zdanovich / B. Punegov, The Experiment in Applying 3D Technology of Magnetic Fields Interpretation at the Archaeological Site "Arkaim". In: K. Ausserer Fischer / W. Börner / M. Goriany / L. Karlhuber-Vöckl (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. BAR International Series 1227 (Oxford 2004) 64–67.

Lieberwirth 2007

U. Lieberwirth, Voxel-Based 3D GIS – Modelling and Analysing Archaeological Stratigraphy. In: B. Frischer / A. Dakouri-Hild (eds.), Beyond Illustration 2D and 3D Digital Technologies as Tools for Discovery in Archaeology. BAR International Series (Oxford forthcoming).

Nigro 1999

J. Nigro, The Swartkrans GIS Project: Using Geographic Information Systems to Explore Cave Taphonomy (Arkansas 1999).

Reilly 1992

P. Reilly, Three-Dimensional Modelling and Primary Archaeological Data. In: P. Reilly / S. Rahtz (eds.), Archaeology and the Information Age. A global Perspective. One World Archaeology 21 (London 1992) 147–173.

Zabulis / Patterson / Daniilidis 2005

X. Zabulis / A. Patterson / K. Daniilidis, Digitizing Archaeological Excavations from Multiple Views. In: Proceedings of the 5th International Conference on 3-D Digital Imaging and Modelling (3 DIM), Ottawa, Ontario, Canada, June 2005 81–88. http://doi.ieeecomputersociety.org/10.1109/3DIM.2005.32 [10 Jun 2006].

Undine Lieberwirth

Humboldt-University Berlin
Institute of Prehistoric and Historic Archaeology
Unter den Linden 6
10099 Berlin
Germany
undine.lieberwirth@web.de