The 3D representation of archaeological stratigraphy and interrelationships of stratified features was described until recently as an illusive goal (e.g. Harris & Lock 1996: 307). This paper takes up this statement as a challenge. The creation of a new module generating voxel-based reconstructions of archaeological stratigraphy paves the way to a new approach in dealing with archaeological data and their spatial analysis. In this paper, a voxel-based structure for obtaining georeferenced, 3D models of archaeological stratigraphy is used at the site of Akroterion at Kastri in Kythera (Greece). The results of this 3D GIS are compared to inferences drawn by the excavators concerning the stratigraphy of the site (Coldstream & Huxley 1972), while a prototype of an Open Source Software (OSS) GIS, which attempts to overcome known limitations of extant OSS, is introduced.

Model-building in archaeology

The raison d’être of archaeology is the interpretation of past human cultural remains, and the reconstruction of 3D objects is frequently part and parcel of archaeological interpretation. The notion of 3D modelling as a means to represent the real world is not new; physical models or maquettes have been the traditional means of gaining a better understanding of the interrelationship of objects in their 3D environment. Geographic Information Systems (GIS), however, offer a more advantageous approach to archaeological modelling. A GIS can handle and access a vast amount of data, but also analyze them in their spatial context on any scale. The broad recognition of GIS as a science, not a mere tool, has created a potential far beyond its originally designated purpose as a cartographic instrument. GIS can be a platform for data retrieval, spatial analysis, the creation of new data through calculation, theory development and hypothesis-testing. Moreover, model-building technology through GIS is advanced enough to enable the reconstruction of excavation data with x, y, z coordinates, as recorded in the field, and the creation of more accurate 3D solid models approximating the real world¹ and suitable for post-excavation spatial analysis. Not only can GIS modelling enable the understanding of the comprehensive structure of archaeological

1. Any model is an imperfect representation of the real world. Abstraction and distortion are intrinsic in the modelling process and derive from many parameters, such as legacy data, technology and software applied, scale and purpose of the model. Choosing the right model for a certain purpose is a vital part of the overall modelling process (Ervin & Hasbrouck 2001: 4).
3D model-building in archaeology

A 3D GIS solid model of archaeological stratigraphy is not aimed at reconstructing the past, but rather building a copy of the archaeological site as it was progressively brought to light through excavation. It allows interactive representation of particular areas, including features, artefacts and layer properties, whilst it allows the exploration of complex information relating to the site’s environment. Such geoscientific visualization should not be conflated with the 3D VR approach (Lock 2003: 152-163), which creates hollow 3D polygon (vector) objects; and hence does not provide inside object information for further analysis in a georeferenced space and contains no quantified background information for statistical analysis.

Solid models

In order to use 2D GIS for the third dimension, it is necessary to create a solid model of the world with inside as well as outside information. These models need to be placed within a real-world 3D space. Therefore, the Cartesian space in GIS has to be extended because

…the limitations of conventional GIS software yield erroneous results. These limitations are based on the fact that conventional GIS packages interpret z values as attributes rather than as true spatial coordinates. (Nigro et al. 2003: 317)

Hence, in a 3D GIS it is essential to handle three coordinate axes independently. For this reason, the third axis needs to be added perpendicularly. Each vector point is then expressed as a triple (x, y, z). This process creates the geometrical background of a volumetric model. Like in an advanced 2D GIS, where vector and raster data can be depicted simultaneously, there are two technical possibilities to create a volumetric model. First, vectors (polygons) can be extended into the third dimension in the Cartesian space to a 3D polygon or polyhedron. The second option is the extension of raster pixel into the third dimension. 3D polygons are the building blocks of VR models. Due to their structure, they do not consist of any inside information and can therefore act only as a 3D masks or hulls, which in turn requires the use of 3D pixels.

3D visualization of archaeological stratigraphy using GIS: a research history

Some pioneering work has already been done in this area by using voxel (3D pixel) technology. Based on the software used, such work can be classified as follows. The first group used commercial software, developed for geological research; the second group developed their own software specifically for archaeological use.

In terms of the first approach, mostly dating to the early 1990s, research has relied heavily on software able to store and analyze 3D volumetric forms (Harris & Lock 1996: 307). At that time, software with the capability of handling graphical databases in combination with relational databases were available mainly for subjects like geology or medicine. The first successful 3D visualization of archaeological stratigraphy employed geological software (Reilly 1992). In another project (Harris & Lock 1996) the utilization of Dynamic Graphic’s Earthvision software enabled the successful visualization of stratigraphical units, their display in categories, the ‘slicing’ of deposits in horizontal and vertical directions, and the calculation of deposit volumes. Later on, in 1999, the Swartkrans pilot project successfully integrated old and new excavation data loaded and analyzed in a GIS. This GIS was furthermore able to discover patterns by using the SPLUS extension. The extension module also applied descriptive statistics for exploiting minimum numbers of individuals or minimum numbers of elements (Nigro et al. 2003: 323). It also became possible to define stratigraphical units using ArcView’s 3D Analyst, ‘slice’ them, calculate their volumes and surfaces; as well as study finds in their...
corresponding context. The complete site’s interior was reconstructed by means of a voxel-based model.

A growing familiarity with GIS applications and the development of faster and all-inclusive technologies eventually gave rise to archaeology-oriented software; the remaining five case-studies (four of which presented at the CAA 2003 conference) exemplify the latter approach. The first among these projects was based on a 3D GIS program designed to meet the needs of archaeological stratigraphy, and combined visualization and hypothesis-testing capabilities with a query tool (Green 2003). Another study (Cattani et al. 2004) explored the differences between two software types in managing 3D data, which were surveyed using a total station; the first produced a voxel model (RochWorks2002, designed for use in geology), the second a vector model (SDRC Surfer). The density distribution of metallurgical slag was visualized; 3D vectors and voxel objects could be visualized simultaneously. In attempting to create a ‘system for 3D capture of a large scale archaeological excavation’ through an architectural case-study, Zabulis et al. (2005) made use of photogrammetry in combination with a total station for georeferencing. The special software designed for this purpose calculated solid voxel models out of the image tuples, thereby maintaining image colours. In a similar vein, Barceló and Vicente (2004) employed a photogrammetric technique for obtaining a georeferenced 3D model of archaeological stratigraphy. Image modification allowed the creation of a 3D geometric model as an adequate representation of archaeological records and, hence, the analysis of taphonomic and site formation processes. Kochnev et al. (2004), on the other hand, modelled archaeological units using geophysical data. They were able to describe the correct location of geophysical anomalies, as well as their depth and distribution; their results were subsequently combined with general archaeological information.

The latest study in the field by Arc-Team (Bezzi et al. 2006) relates to the creation of a voxel model of archaeological stratigraphy using the OSS programs GRASS GIS, Blender and ParaView. They used the GRASS GIS module r.to.rast3 to create voxels, yet they describe their model as ‘hollow’ rather than a ‘real voxel’.²

It is evident that the commercial software are the most powerful ones (e.g. Cattani et al. 2004). However, specialized software compare favourably with the former in terms of the advanced results achieved. In one case (Kochnev et al. 2004), such specialized software even enabled a depiction of interpolated voxel values. In general, the above case-studies show the usefulness and great potential of a 3D GIS approach to archaeological data. Remarkably, none of these packages were used in follow-up projects. The user-unfriendly interfaces of 3D GIS software in general and a focus on analysis rather than visualization (Lock 2003: 152) might have something to do with this. But since the source codes of the above specialized software were not revealed, as with their commercial counterparts, it is likely that the lack of continuity also has to do with the fact that they did not run under the OSS licence and therefore were not easily available for further projects. Needless to say, complete insight into the underlying processes of such software is vital for scientific applications. The study of these previous steps towards 3D GIS helped articulate my principle research aim, which is to overcome the shortcomings of hitherto applied software in the field.

**Voxel structure and creation**

The term ‘voxel’ is a combination of the words ‘volume’ and ‘pixel.’ A voxel, in essence a 3D pixel, is a volume element which can be sliced or exploited for the creation of iso-surfaces. Like a pixel, a voxel can contain one scalar numeric (w-) value, like colour, category, density, or geostatistical values like mineral values, precipitation, air pressure etc. Voxels are able to represent an inside and outside world, as well as build the quantified basis

². The raster maps were stretched perpendicularly up to a defined boundary, e.g. a second raster map. The voxel created this way does not contain any new information, i.e. a fourth value (w-value, see section ‘Voxel structure and creation–Interpolation’) for further analysis. Hence this extension is graphical rather than quantified.
for numerical analysis and statistics. They are therefore indispensable to 3D GIS modelling. At present, there are two ways to create a voxel, interpolation and ‘flood-filling’.

Interpolation

As with interpolation algorithms in 2D [Figs. 1-2], it is possible to interpolate vector points in a 3D space. The 3D algorithm works in the same way, but with the addition of the third dimension [Fig. 3]. The 3D interpolation algorithm, for example Nearest Neighbor, Spline etc., interpolates between the 3D vector points. Unlike 2D interpolation, however, the value which is interpolated is not the z-value (normally elevation) but the w-value. The w-value, like the z-value in 2D, is defined as an attribute. These attribute values have to be expressed as floating-point numbers which are normally provided by measurements. The 3D interpolation creates fuzzy transitions [Fig. 4] and is therefore suitable for vague strata boundaries.

Flood-filling

Unlike interpolation estimating the value within two known values by using a mathematical function, the algorithm of the flood-filling process fills the 3D space between defined boundaries with voxels [Figs. 5-7]. Using this method, we can create categorical volume grids with clear boundaries. This approach is best suited to clearly defined stratigraphical units. Since ‘for the stratigraphic record the deposit is reduced to a unique number in the stratigraphic sequence’ (Doneus & Neubauer 2004: 113), this method is suitable for creating archaeological units with arbitrarily allocated context numbers and for modelling strata with numerical labels.

An OSS 3D GIS

Since a suitable OSS GIS module for creating real voxel-based models of archaeological stratigraphy does not yet exist, I utilize the new GRASS GIS module r.vol.dem (courtesy of B. Ducke), which takes advantage of the flood-filling process. In combination
with the visualization software ParaView, this software can certainly compete with other software packages mentioned earlier. The module’s objective is to handle ordinal numerical expressions of archaeological units in order to create 3D volume grids of archaeological stratigraphy. This new module is able to calculate voxel maps between at least two digital elevation models (DEMs). The flood-filling algorithm adjusts the same label value (w-value) to each voxel per 3D unit.

The Akroterion case-study

Legacy data

Trench IX of the Akroterion excavation (Coldstream & Huxley 1972) was chosen because it provided the greatest amount of input data with two cross-sections (unlike other trenches) and one plan drawing [Figs. 8-10]. Trench IX features a complex stratigraphy of 12 units dating from the Middle Minoan IB period to Byzantine times, as well as architecture from different periods. Wall α [Figs. 8-9] forms the outer wall of the ‘West House’, which borders three superimposed walking surfaces: Unit Surface 3 (Late Minoan IB), Unit Surface 11 (Late Minoan IB) and Unit Surface 12 (Middle Minoan III). The ‘West House’ and therefore wall α was dated to the Late Minoan IB period. The surfaces in question were destroyed to the west by the Byzantine wall β, which had roughly the same orientation as wall ε beneath it [Fig. 10, Plate 13].

3. This is one of the three Late Minoan IB houses on the site (North, South and West House).
4. This feature does not show in the paper drawings (Simpson & Lazenby 1972: 57).
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Byzantine occupation destroyed a great part of Unit 7 (Simpson & Lazenby 1972: 57-58).

The voxel-based model

All stratigraphic elements within Trench IX were transformed into 3D voxel-based objects through the GRASS GIS module r.vol.dem mentioned earlier; the result was visualized through the software ParaView [Plate 11-16]. Not only did it become possible to confirm the excavators’ interpretations in this way (Simpson & Lazenby 1972); additional information about the trench was furnished. For example, the orientation of the unit surfaces [Plates 14-15] and the walls inside the trench became more easily perceptible, while the various architectural fragments could be measured precisely at any point in 3D space. The latter task was quite difficult for the excavators, since wall width varied considerably between the two documented cross-sections.

Occupation phases

The stratigraphy was not described in adequate detail by the excavators, so that a comprehensive comparison with the results of this paper is not possible. However, some new inferences can be drawn on the basis of the following actions: a) the exact volume of each stratigraphical unit was calculated according to the cell counts of the voxel-based stratigraphical models [Table 1], then compared with each other; b) the process of construction of the architectural features within Trench IX, as well as the occupation phases in a relative chronological order, were clarified.

The 3D GIS model of the Trench IX features suggests that the first occupation took place with the construction of walls γ, δ and ε, which are part of Unit 10 (Middle Minoan IB–IIIA periods) [Figs. 8–10 and Plate 11, light green colour]. This first occupation postdates Units 13-14 [Plate 11, dark brown and dark green colours], which are not dateable and might not even have resulted from human activity. Walls γ, δ and ε, of Unit 10 are superimposed by Unit 8 [Plate11, brown colour], which roughly dates to the same

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<table>
<thead>
<tr>
<th>Period</th>
<th>Stratigraphic units</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM</td>
<td>8, 10, 12</td>
<td>12.57</td>
</tr>
<tr>
<td>LM</td>
<td>3, 7, 11, 15</td>
<td>7.6</td>
</tr>
<tr>
<td>Byzantine</td>
<td>4</td>
<td>6.83</td>
</tr>
<tr>
<td>Modern</td>
<td>2</td>
<td>17.54</td>
</tr>
</tbody>
</table>

Table 1. Volume calculation of deposits within Trench IX

Figs. 5-7. Flood-filling process.
Fig. 8. Kythera, Kastri, Akroterion Trench IX, north section (after Simpson & Lazenby 1972, fig. 20).

Fig. 9. Kythera, Kastri, Akroterion Trench IX, south section (after Simpson & Lazenby 1972, fig. 21).

Fig. 10. Kythera, Kastri, Akroterion Trench IX, plan of Minoan walls (after Simpson & Lazenby 1972, fig. 22).
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period. Thus, they belong to structures that were in use for only a short period of time. Unit 8, on the other hand, consists of remains from several periods without stratigraphic interruption, which suggests a continuous occupation at the site after the first habitation phase. The site remained in use following the long Middle Minoan period (ca. 200 years, represented by Units 8, 10 and 12). This is demonstrated by the paved area belonging to Unit 11 (Late Minoan IA period, refurbished in Late Minoan IB). Unit 7 lies atop the Middle Minoan Unit 8 [Plate 11, light orange colour].

Since Unit 7 dates to the Late Minoan IB period, we can conclude that Unit 8 was not covered up in the Late Minoan IA period. Units 3, 7 and 15, also dating to the Late Minoan IB period, are associated with the ‘West House’ (represented by walls α and α1). Based on the publication, there is no evidence for post-Minoan habitation other than the much later reoccupation of the site during the early Byzantine era. The destruction of Minoan strata by the later occupation is evident in the ‘negative’, lower part of Unit 4 [Fig. 14], which can be only the result of human activity. The upper part of Unit 4 [Fig. 15], however, could be due to erosion.

Volumetrics

The deposit volume of the Middle and Late Minoan periods together was three times greater than that of Byzantine period⁵ [Table 1]. Since the parts of the Minoan and Byzantine periods at issue are of the same duration approximately (ca. 200 years), it would appear that there was a much greater activity during the Middle Minoan period, at least at this site, than in Byzantine times.⁶ It is also evident that the Late Minoan occupation left fewer traces than the Middle Minoan ones, arguably due to its shorter time interval. Finally, the deposit volume calculation clearly shows that the modern stratum (Unit 2)’ represents the largest volume [Plate 11, orange colour].

Conclusion and future work

Every excavation fills gaps in the puzzle of the past. The same is true for post-excavation analysis. Reconstructions and models of a site are not just a means to store, combine and present recorded information, but they can also help articulate and convey additional information implicit in the data. Such models allow a better understanding of the interrelationship of strata in its 3D environment and more comprehensive investigation of the site. As with a simulation, a geometric and dynamic model permits better control of variables and parameters (Blankholm 1991: 55). Thus, I would agree that “for the real 3D documentation and analysis of future archaeological excavations, the use of Voxel will become indispensable!” (Bezzi et al. 2006: 29).

This paper shows how archaeological information can be retrieved, for instance in terms of volumetric and spatial analysis, while it also demonstrates the advantages of the 3D approach in tackling spatial problems in archaeological stratigraphy. The utilization of GRASS GIS and ParaView in combination presents the following principal advantages, in particular:

- Each stratigraphical unit can be depicted separately, which in turn allows the reconstruction of taphonomic, accumulation and erosion processes in 3D [Plates 13, 15]. Deposits can be visualized by category (e.g. period, soil type, colour etc.) [Plates 11-12]. Implicit spatial patterns can emerge in this fashion.
- The complete stratigraphy over the entire trench width can be displayed, which may reveal ancient surfaces not hitherto perceptible [Plates 14-15].

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5. In this calculation I do not take into account destroyed volume, which could be estimated and added in a future project (see below).

6. In order to be reliable, such volumetric comparisons generally ought to take into account factors such as erosion, the nature of the deposits in question, building materials used for structures etc.

7. Unit 2 was not investigated in detail.
Stratigraphic sequences can be visualized in relative and absolute chronological order; by creating a time series, the 3D GIS therefore converts into a 4D GIS.

The excavation can be recreated virtually, step-by-step, through horizontal 'slicing' at any level. Horizontal, vertical and diagonal slices are possible, offering insight into deposit structure [Plate 12]; such slices make it possible to disregard the original, conventional excavation layers and to follow the strata in their natural form and thickness.

3D data (architecture, pits, postholes, and artefacts) can be mapped in 3D georeferenced space and retrieved according to their numeric label [Plate 16]. Deposits can be compared [Table 1] and analyzed for volume, extent, shape and size. This makes the 3D GIS approach ideal for heritage management.

Measurements, such as stratigraphic depth (even within a single layer) and distance between two points, can be taken in Euclidean space.

The outcome can be described as a ‘3D interactive geographic map’ of archaeological stratigraphy. Notably, the above list is far from exhaustive; further advantages may arise through the application of this method on a different set of data. The implementation of 3D statistics, query functionality, the ability for multitrench visualization and analysis (including analysis of erosion and accumulation processes), the inclusion of predictive modelling features and a complete shift to OSS software are areas worthy of future work and development.

Bibliography


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