ELSEVIER

Journal of Archaeological Science 35 (2008) 655–667

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

A 3D digital workflow for archaeological intra-site research using GIS

Markos Katsianis [a,*], Spyros Tsipidis [b,**], Kostas Kotsakis [a], Alexandra Kousoulakou [b]

[a] *Department of History and Archaeology, Aristotle University of Thessaloniki, Greece*
[b] *Department of Cadastre, Photogrammetry and Cartography, Aristotle University of Thessaloniki, Greece*

Received 14 March 2007; received in revised form 24 May 2007; accepted 3 June 2007

Abstract

Across a range of archaeological projects in Northern Greece, a context-based system, which has much in common with similar stratigraphic methods applied elsewhere in the world, is in use to record the excavation process. Here, we discuss a formal data model and complete digital workflow for the documentation of this process in 3D using the prehistoric site of Paliambela Kolindros, Greece, as a case study. The entire digital process has the advantage of being implemented on a single software platform. In addition, the combination of formal ontology and custom object-oriented programming enables a suite of techniques for exploratory data analysis and stratigraphic interpretation.

Keywords: Excavation; GIS; 3D models; UML; CIDOC-CRM

1. Introduction

During the past 10 years, a range of prototype, bespoke and/or commercial applications for the digital documentation of excavation have been developed in different countries and on the basis of distinct fieldwork practices (for a review see Kvamme, 1999: 164–167; Lock, 2003: 78–123. Also, Clarke et al. (2003) and Powlesland et al. (1998) provide some interesting examples on information flow through to publication). Although the functionality that these provide is gradually improving, a more active role for such digital methods in the actual process of archaeological interpretation is still pursued. Digital datasets can encourage reflexivity in the excavation process, as they enable easier correlation, re-assessment and re-assembly of fragmented information in the excavation archive (Hodder, 1999: 178–188; Roskams, 2001: 267–287). The use of GIS to integrate excavation recording procedures, data management, digital object representation and spatial analysis, ideally could lead to the formation of a complete digital workflow for archaeological documentation. Towards this end, we focus on the combination of three critical elements: (i) the development of an explicit data model for georeferenced archaeological data, (ii) effective recording and handling of spatial entities in 3D and (iii) the development of 3D tools for intra-site analysis. The approach described here is based on an explicit semantic and geospatial model and a relatively transparent development environment (ArcObjects) that allows communication with different software platforms and is potentially open to further adaptation and customization by other users.

2. Context of study

Perez (2002) emphasizes the fact that existing information systems for cultural resource management have focused on producing bits of custom-built functionality without necessarily grounding these on well-established computer science tenets, such as domain definition and system development methodologies (for an explanation of these terms see Dennis

---

* Corresponding author.
** Corresponding author.
E-mail addresses: markoskatsianis@hist.auth.gr (M. Katsianis), stsipidi@topo.auth.gr (S. Tsipidis).

0305-4403/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2007.06.002

et al., 2001). In addition, the application of GIS in excavation practice has been hindered by the difficulties associated with handling 3D spatial entities and incorporating the temporal dimension into digital archaeological information (Wheatley and Gillings, 2002: 233−236).

2.1. Data models for archaeology

Archaeological observation proves to be very complex to model in database terms as it presents a broad variety of analytical objects, concepts and actions that are related in a wide variety of ways (Madsen, 2003). During the research process both relations and object definitions require re-adjustments as new conceptual categories (e.g. a broader stratigraphic group or phasing) emerge as part of the interpretive process. Furthermore, typological constraints and uncertainty about basic material properties (e.g. colour or chronology), caused either by the differences in excavation recording methods or simply the subjective nature of archaeological description, make the task of defining archaeological units and their characteristics even more complex. Finally, the implementation of an excavation data model within a georelational data framework requires advanced linkages between textual and graphical information (D'Andrea, 2003). Despite these restrictions, the use of object-oriented conceptual modelling and the development of explicit ontology models with spatio-temporal elements, such as the CIDOC-CRM ISO 21127 (Doerr, 2003), can place the excavation process in a more structured analytical and semantic domain.

2.2. Can intra-site GIS move to 3D?

Strongly connected with these problems are the current limitations in representing excavation data within a GIS. Most systems for excavation data management are largely two-dimensional and depict information by a series of overlaying context plans. The actual excavation contexts are either missing or are drastically simplified in 2D. Although 2D spatial analysis in current commercial GIS packages is efficient, the provision of 3D functionality is a complex issue both from a practical and theoretical perspective. 3D GIS functionality aspects, such as object manipulation, geometry and topology, are still not embedded in current GIS systems (Zlatanova et al., 2002). As a result, 3D representation of stratigraphic contexts in GIS has been a major concern since the mid-1990s (Lock, 1995; Zhukovsky, 2002; Barceló et al., 2003; Barceló and Vicente, 2004). In a recent paper Losier et al. (2007) provide a thorough discussion on 3D excavation unit modelling methods.

Several criteria should be taken into account in order to choose the most suitable spatial data model. Many researchers propose 3D grid representation (*voxels*) as the most appropriate data format for handling volumetric entities and visualizing continuous phenomena (Cattani et al., 2004; Bezzi et al., 2006). However, their incorporation in a GIS environment is still problematic in both simple display and overall management as—being scale-specific—they demand large numbers of survey points in order to achieve an appropriate resolution, tend to produce very large data files (Cattani et al., 2004; Losier et al., 2007: 282) and present difficulties with multiple attribute relations. Alternative ways of constructing 3D objects are provided by Constructive Solid Geometry (CSG) or 3D boundary representation (B-rep). CSG objects can build up more complex shapes by combining 3D spatial primitives, e.g. cylinders, spheres, cubes (Jarroush and Even-Tzur, 2004). However, the irregularity present in archaeological stratigraphic entities makes their application ineffective. In the last decades, 3D boundary representation modelling has been studied intensively. B-reps reveal some important advantages in terms of construction and GIS management. The boundaries of such objects can be easily constructed by relatively few measurements taken on the field, while their shape accuracy is related to the survey precision without necessarily having a great impact on the file size. In addition, they can be effectively linked to the attribute data through an appropriate georelational system (Apel, 2004: 27−32; Stoter and Zlatanova, 2003a). Although they do not provide direct volumetric information, geometrical algorithms can be applied for this purpose (Losier et al., 2007: 284).

2.3. Placing an emphasis on temporal data

Additional requirements are placed on GIS functionality, since the investigation of material culture transformations through time is one of the primary goals of archaeological research. Although temporal reasoning has only recently been given a theoretical focus in archaeology (Gosden, 1994), already many researchers stress the fact that the linear, objective and irreversible notion of time that is maintained in field archaeology should be replaced by more flexible approaches that incorporate the concepts of multiple temporal paths, different time-scales and the prospect of non-linear trajectories (Bailey, 1983; Castleford, 1992; Lucas, 2005).

Within GIS, most research on spatiotemporal databases is linked to the modelling of dynamic phenomena, i.e. temporal data representing constantly changing events in the present. Despite ongoing research in spatio-temporal database systems (Sellis et al., 2003) and geovisualization techniques (Dykes et al., 2005), the implementation of the temporal dimension in spatial databases and support for truly temporal analysis of GIS data has not been effectively achieved in most GIS systems (Constantinidis, in press). Within a 3D GIS environment temporal data modelling and representation is even more difficult, because the available tools are limited to relatively trivial features such as time-stamping and temporal animation techniques.

Excavation data differ from dynamic temporal phenomena in the sense that they represent events or durations that have to be organized both in a relative or absolute manner, and with more or less interpretive certainty (Constantinidis, in press). A major issue in archaeological reasoning is the temporality of material objects or, to put it more evocatively in the words of Olivier, 2004: 206), the fact that *''Material things embed themselves in all subsequent presents''*. An artefact can, therefore, have multiple temporal values depending on the date of its production, use, deposition or recovery. Shanks and Tilley, 1987: (118–136) maintain that the significance of temporal reasoning in excavation is the reduction of difference by identifying temporal data sequences and the production of meaningful chronological statements. In the first case, temporal sequences can be related to the concept of stratigraphy, while in the second, chronological meaning can be related to the deciphering of material temporality. The fundamental conclusion to draw from all of this is that, to support temporal reasoning effectively, excavation databases must incorporate both multiple sets of temporal values for archaeological material and a range of carefully designed tools for temporal classification and exploration.

3. Excavation as an analytical domain

Object-oriented software development methods such as those offered by the Unified Modelling Language (UML) (Dennis et al., 2001) allow analysis of a chosen application domain in conjunction with the iterative and incremental modelling of any proposed implementation through a series of diagrammatic depictions. UML can provide a systematic way to acquire knowledge about the domain of excavation practice that incorporates, not only what is documented during fieldwork, but also how the archaeological reasoning process combines known data and further observations during later stages of analysis. The means to perform the analysis are a series of use-case scenarios (formal descriptions of the domain processes) that provide an account of excavation workflow and post-excavation study.

3.1. Excavation practice at Paliambela Kolindros

The excavation and recording methods at Paliambela (Fig. 1) are part of a wider approach in use by several archaeological projects in Northern Greece and present strong similarities to many other context-based recording systems throughout the world (see Roskams, 2001). Their particular traits have been described in more detail elsewhere (Kotsakis, 1989; Katsianis et al., 2006; Kotsakis et al., in press): to summarize briefly, the archaeologist tries to follow the extent and limits of each stratigraphic deposit, but is able to subdivide their investigation into smaller arbitrary excavation units, based on observed differentiations (e.g. in the soil texture, moisture or inclusions), until the deposit is removed to its full observable limits. This process of deposit subdivision presents advantages in the gradual removal of the layer, the limitation of material contamination, ease in material management and most importantly, subsequent re-evaluation of the excavation process based on other criteria (i.e. the revealed section). However, it presents some drawbacks, since spatial and attribute information about a deposit is further compartmentalized into a collection of small units. In addition, the excavation archive goes through a process of further fragmentation during post-excavation study (Jones, 2002). During this stage, distinct material categories (e.g. different find categories) are distributed among specialists in order to carry out individual studies and provide feedback that can aid later stratigraphic analysis. The above practices can make stratigraphic reconstruction a more difficult task due to the complexity of the records associated with every excavation entity.

3.2. Domain analysis of excavation practice

The use case analysis demonstrated that the main advantage of the methodology in Paliambela is the linkage of attribute information to discrete objects defined by the archaeologist. These objects form the basis for every new interpretive entity that is created through the process of stratigraphic analysis and post-excavation study. It seems then that the object-oriented paradigm is particularly appropriate for modelling the excavation domain and is favoured here for both data organization and representation. In addition, documentation and recording during fieldwork proved to be a relative standardized process, in contrast with post-excavation study. The fragmentation of the excavation archive among the specialists discourages the

Fig. 1. The excavation site of Paliambela Kolindros Greece.

interpretive engagement with the totality of the site (see also Jones, 2002). To overcome this situation, the excavation archive should present a basic level of documentation and the ability to structure the database further in response to the interpretive process and specialist feedback.

3.3. Implementation platform

Esri's ArcGIS was chosen as the unifying software platform for several key reasons: (a) being an industry standard, (b) incorporating a functional 3D viewing environment (ArcScene), (c) presenting abilities for customization, (d) having a spatial database system with object-oriented characteristics and (e) supporting communication with external programs (RockWare, EVS, CAD, Sketch Up). In the lack of advanced Spatial Database Engine (SDE) license a personal geodatabase using MS Access was employed. In terms of application design software, MS Visio was used for the drawing of the system's data model, as it presents XML export capabilities to ArcGIS. We feel, however, that it could be extremely useful to explore the potential of open-source implementation as it can overcome the problems of low budget that most excavation research projects usually experience.

4. Excavation data model

As described by Arroyo-Bishop and Lantada Zarzosa (1995) "archaeology is an object-space-time relationship that needs to manage all three of these factors in order to arrive at valid conclusions". GIS can be described as a means to exploit structured linkages between thematic and spatial or temporal data. The model presented below is organized around these three axes.

4.1. Thematic data organization

The data model was based on the definition of some key points of reference that emerge from the use-cases, the analysis of existing paper recording forms and past conceptual data models (Hadzilakos and Stoumbou, 1996). Basic concepts associated with the archaeological process were defined in UML with reference to the CIDOC-CRM ISO 21127 standard (Crofts et al., 2005). Its adoption from the early stages of the project aimed primarily to provide an explicit account of the terms used in the data model and show the conceptual relationships that exist between the data. A second reason was to allow us future scope to assess, critically and pragmatically, the oft-advertised advantages that semantic interoperability is supposed to bring to the internet delivery of excavation data. Design patterns from the ontological model of the workflow of the Centre for Archaeology (Cripps et al., 2004), have been used in order to achieve semantic compatibility and provide a degree of accordance between different excavation methodologies (Fig. 2). The mapping of these basic concepts and their relationships in a UML class diagram allowed the definition of specific behaviour and rules that can be linked to spatial entities in a GIS database. The concepts were implemented as object classes whose instances present object-oriented characteristics, such as generalization, aggregation and inheritance (Conolly and Lake, 2006: 51–60)[1] (Fig. 3).

Stratigraphic analysis and chronological phasing reflect a process of context grouping (Clark, 2000, Roskams, 2001: 257–261; Herzog, 2004). By incorporating a hierarchical aggregation mechanism within the data model, the database can aid stratigraphic reasoning via a series of grouping stages. The data model allows low classes (e.g. excavation unit/feature) to be aggregated on the basis of archaeological criteria to interpretive high classes (stratigraphic layer/feature group). When the new higher class element is created and populated with attribute data, all the component classes inherit its characteristics (e.g. stratigraphic relations). The organization of stratigraphic reasoning through an aggregation process allows the re-examination of excavation work and endows the archaeologist with a way to literally reconstruct the site in its entirety. It provides a further advantage, since the recorded information during fieldwork is left intact and all interpretive comments during post-excavation study are retained in higher level classes. By relating all primary remarks concerning the reasoning behind an action of interpretation (e.g. context identification or deposit grouping) to the particular archaeological entity that is the outcome of this process, a record of interpretive reasoning is imbedded within the database and not kept elsewhere (e.g. in external reports or video recordings).

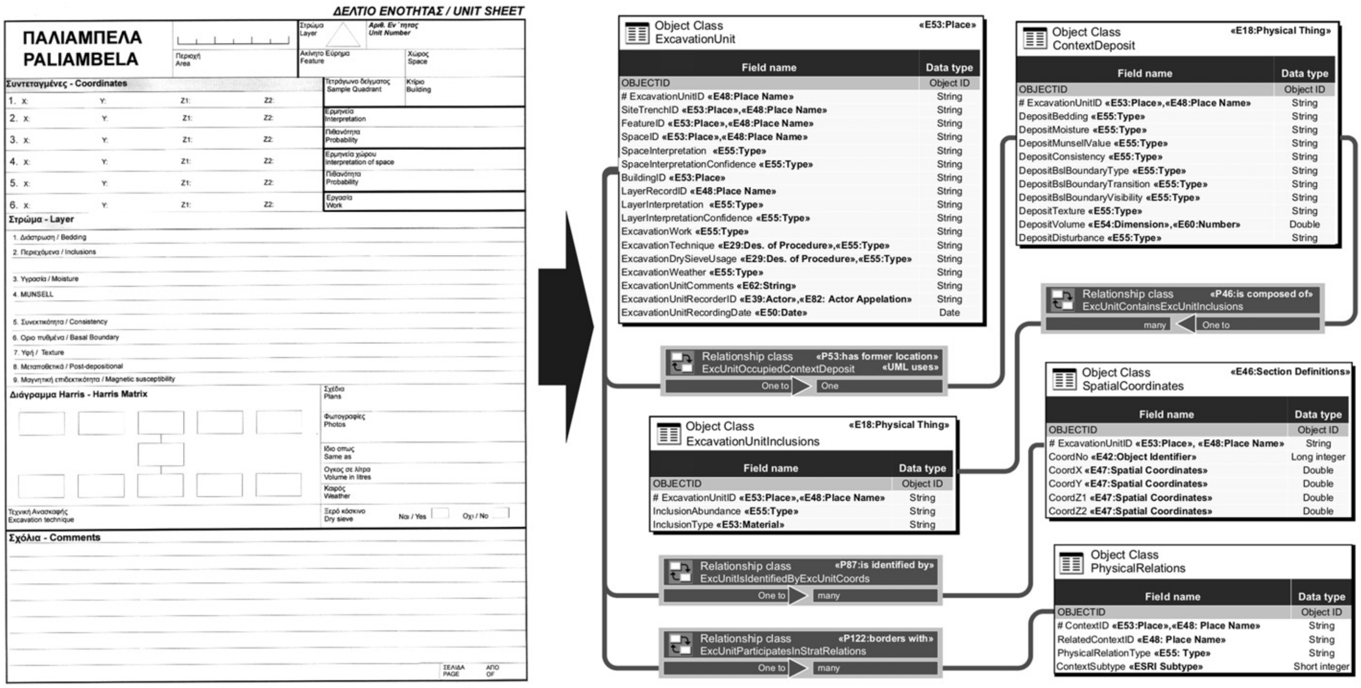
The properties defining in each class of the data model are left as simple as the initial level of recording in the field and not extended to all sub-domains of specialist analysis (e.g. pottery, food-residue study). Data tables that contain basic information can be exported to other programs, where specialists can add remarks or perform additional analysis. Their observations can be re-imported in the database and visualized or classified accordingly.

4.2. Spatial data types

However, for a GIS to operate effectively, basic elements of the defined classes have to be represented spatially. For our purposes we define seven basic spatial elements of archaeological information that can be represented as 3D vector features. Most represent actual objects in the real world, such as a feature or a find, whereas others are a conceptualization of archival events that occur during recording, such as an excavation unit, a drawing or an orthophoto. They provide the basic elements around which archaeological information is collected. Their 3D graphical representation is crucial for the exploration of information in a GIS environment (Stoter and Zlatanova, 2003b). Subsequent spatial groupings that occur during post-excavation study, such as more complex stratigraphic layers

---

[1] So far polymorphism (i.e. multiple object inheritance), a very important characteristic for modelling archaeological data, has not been implemented in most spatial databases.



Object Class «E53:Place»
ExcavationUnit

Field name	Data type
OBJECTID	Object ID
# ExcavationUnitID **«E48:Place Name»**	String
SiteTrenchID **«E53:Place»,«E48:Place Name»**	String
FeatureID **«E53:Place»,«E48:Place Name»**	String
SpaceID **«E53:Place»,«E48:Place Name»**	String
SpaceInterpretation **«E55:Type»**	String
SpaceInterpretationConfidence **«E55:Type»**	String
BuildingID **«E53:Place»**	String
LayerRecordID **«E48:Place Name»**	String
LayerInterpretation **«E55:Type»**	String
LayerInterpretationConfidence **«E55:Type»**	String
ExcavationWork **«E55:Type»**	String
ExcavationTechnique **«E29:Des. of Procedure»,«E55:Type»**	String
ExcavationDrySieveUsage **«E29:Des. of Procedure»,«E55:Type»**	String
ExcavationWeather **«E55:Type»**	String
ExcavationUnitComments **«E62:String»**	String
ExcavationUnitRecorderID **«E39:Actor»,«E82: Actor Appelation»**	String
ExcavationUnitRecordingDate **«E50:Date»**	Date

Object Class «E18:Physical Thing»
ContextDeposit

Field name	Data type
OBJECTID	Object ID
# ExcavationUnitID **«E53:Place»,«E48:Place Name»**	String
DepositBedding **«E55:Type»**	String
DepositMoisture **«E55:Type»**	String
DepositMunsellValue **«E55:Type»**	String
DepositConsistency **«E55:Type»**	String
DepositBslBoundaryType **«E55:Type»**	String
DepositBslBoundaryTransition **«E55:Type»**	String
DepositBslBoundaryVisibility **«E55:Type»**	String
DepositTexture **«E55:Type»**	String
DepositVolume **«E54:Dimension»,«E60:Number»**	Double
DepositDisturbance **«E55:Type»**	String

Object Class «E18:Physical Thing»
ExcavationUnitInclusions

Field name	Data type
OBJECTID	Object ID
# ExcavationUnitID **«E53:Place»,«E48:Place Name»**	String
InclusionAbundance **«E55:Type»**	String
InclusionType **«E53:Material»**	String

Object Class «E46:Section Definitions»
SpatialCoordinates

Field name	Data type
OBJECTID	Object ID
# ExcavationUnitID **«E53:Place», «E48:Place Name»**	String
CoordNo **«E42:Object Identifier»**	Long integer
CoordX **«E47:Spatial Coordinates»**	Double
CoordY **«E47:Spatial Coordinates»**	Double
CoordZ1 **«E47:Spatial Coordinates»**	Double
CoordZ2 **«E47:Spatial Coordinates»**	Double

Object Class
PhysicalRelations

Field name	Data type
OBJECTID	Object ID
# ContextID **«E53:Place»,«E48: Place Name»**	String
RelatedContextID **«E48: Place Name»**	String
PhysicalRelationType **«E55: Type»**	String
ContextSubtype **«ESRI Subtype»**	Short integer

Fig. 2. Digital implementation of the data fields found in a paper context recording sheet showing their relationship to CIDOC-CRM entities.

or phases, can be represented by their constituting elements, the excavation units and features respectively (Fig. 4).

4.3. Temporal data inclusion

Extending the observations made by Koussoulakou and Stylianidis (1999) about the temporal categories used in an archaeological excavation we have identified six temporal paths when describing archaeological data that can be incorporated in a database system through time-stamping as events, durations or relative temporal relationships (Table 1).

These categories apply to different sets of archaeological data, but can be used to assign chronological character to a deposit. They have been incorporated in the database as timestamps so that they can be inherited or assigned to different sets of data. For example, an excavation unit recorded on 25/5/2003, is created as an entry in the database on #25-05-2003 00:00:00#, is assigned to Late Neolithic based on pottery typology, contains a ^{14}C sample that dates the deposit to 4700 BC (around which lies a probabilistic envelope of uncertainty), is part of a group layer that is later than another group layer assigned to Middle Neolithic and is associated with Phase IV of the excavation record. Depending on the archaeological question, the proper set of temporal attributes are used to classify the excavation data (Fig. 5).

5. From field recording to object construction

The way objects are constructed in a GIS environment will inevitably be strongly related to the recording methodology used in an excavation. At Paliambela, the excavation grid was based on the Greek national coordinate system and provided the basis for both the spatial recording of the excavation and the creation of a Digital Elevation Model (DEM) of the site area. The location and extent of archaeological entities are recorded by total station and the production of ground plans and sections is facilitated considerably by 2D photogrammetry (Patias et al., 2005).

5.1. Producing 2.5D raster surfaces

Raster data types initially provide the basis for all plans, sections and digital photos. At the same time, a set of point measurements is taken over the entire excavated area (following the recording suggestions by Cattani et al., 2004: 300), and a DEM is created using the IDW 12 interpolation procedure with breaklines[2]. Mosaics of the raster data can then be fully georeferenced and displayed with *Z* values directly from the DEM. However, since spatial databases present limitations in the effective management of such complex representations, and after some experimentation (see Katsianis et al., 2006), we have decided *not* to embed these in the main excavation geodatabase and instead use hyperlinks to the raster data sources which contain predefined display and symbology settings (Fig. 6a).

5.2. Producing 3D vectors

In many ways more important to our purposes has been the reconstruction of most excavation entities as 3D vector

---

[2] This procedure gave the best results during the testing of various interpolation algorithms.

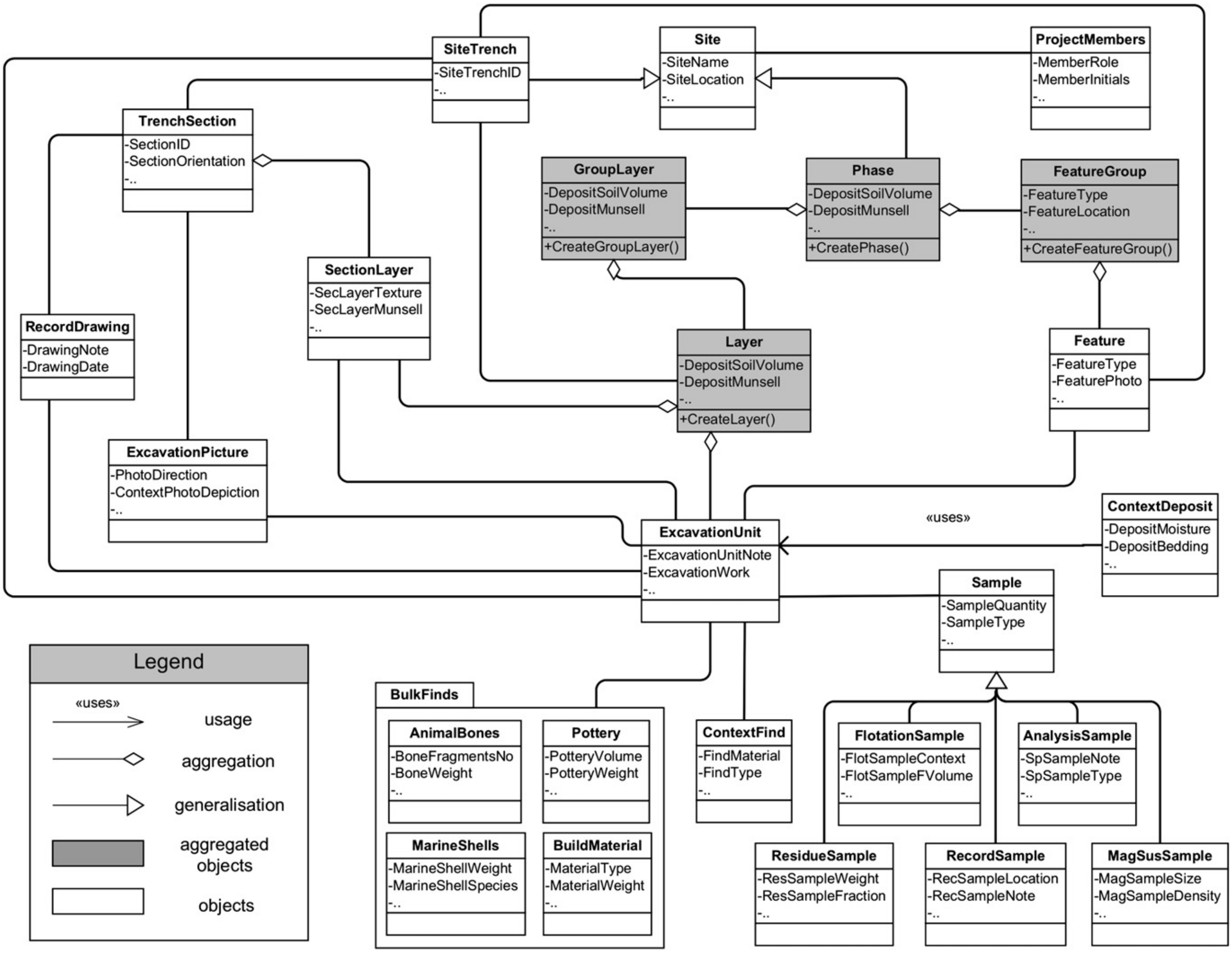


Fig. 3. Object class diagram defining relationships in a typical excavation workflow.

features from their recorded spatial coordinates. In this respect, the GIS platform currently preferred for our work at Paliambela (ArcGIS including ArcObjects and ArcScene) supports 3D *point*, *line* and *polygon* vectors as well as 3D *multipatch* b-rep objects (ESRI, 1998: 20−25).

More precisely, the site trenches are visualized as 3D lines or polygons that gain their *Z* value from the excavation area DEM. Finds and samples are recorded using single *X*, *Y*, *Z* coordinates and thus can be represented as 3D point data (Fig. 6b). Plan drawings are multipart linear features that also receive their *Z* values from the DEM of the recorded area (Fig. 6c).

Excavation units are particularly difficult to model as they represent volumetric spatial entities with irregular shape.

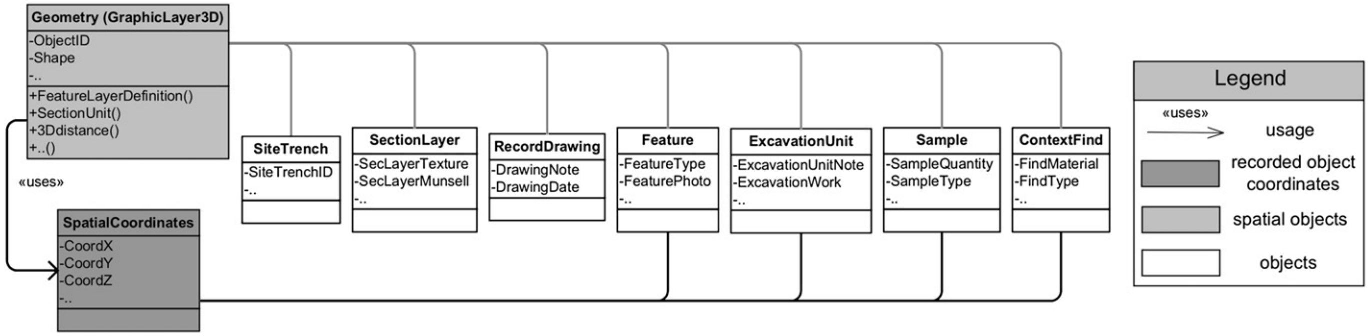


Fig. 4. Spatial class diagram.

Table 1
Temporal categories recorded as timestamps

Temporal categories	Description	Temporal Concept	Examples
Excavation time	Recording time	Event	25/5/2003
Database time	Creation time in the information system	Event	#25-05-2003 00:00:00#
Stratigraphic time	Relative temporal distinction between deposits	Relative position	Layer X > (Is Later Than) Layer Y
Archaeological time	Cultural temporal categorization	Duration	Late Neolithic
Site phase time	Excavation chronological framework	Duration	Phase IV
Absolute time	Absolute chronology	Event	4700 BC+/− 150 years

All or some of these temporal paths apply to different excavation objects depending on the interpretive objectives.

Initially, we developed a method for constructing excavation units using geological visualization programs that could be exported to GIS as contiguous multi-part polygon objects (Tsipidis et al., 2005). However, their large file size and the inability to be treated as single objects within the database made them insufficient for our purposes. An alternative construction method was therefore developed that allows the production of multipatch entities from individual measurements through a programming routine (Fig. 6d). The proposed method fulfills the need for direct 3D object creation as the 3D excavation unit object can be rapidly created and stored in the database, even during fieldwork. At present, due to the individual modelling of each excavation unit, a level of shape simplification still occurs that can result in slight overlaps or empty areas in between. The use of better surveying equipment (e.g. laser scanners) could minimize these effects. Major empty spaces and extensive overlaps are indicators of plotting mistakes made during fieldwork or the process of digital data input, and can be minimized by careful modelling.

Finally, more complex objects, such as archaeological features (Fig. 6e) or section layers (Fig. 6f), can be constructed through the use of 3D CAD software and become incorporated in the spatial database as complex multipatch objects through supported import routines (Tiede and Blaschke, 2005). In this case the level of detail is again related to the available surveying equipment (Fig. 7).

A key advantage of this approach is that the 3D vector primitive for each archaeological unit is recognized as a single object within the GIS environment (unlike the case that would pertain for TIN or voxel models of archaeological surfaces) and implies a one-to-one correspondence between a record in the database and an object in the graphical environment.

5.3. Depicting 3D vector objects

The comprehensive display of archaeological data in a 3D environment requires strategies for the use of appropriate symbology. Simple 3D point markers (e.g. tetrahedron, cube, cone, sphere, etc.) and other cartographic elements such as colour ramps (e.g. Munsell colour values), textures (i.e. soil texture icons) and transparency can be used from within several GIS applications (e.g. Grass, NVIZ, MapInfo, ESRI ArcScene). More complex custom symbols can be created in various software platforms (3D studio, Open Flight, Sketch Up, VRML) and enhance 3D representation. Finally, 3D text labelling can also facilitate the understanding of the displayed scene by creating identifiable reference points. Despite these existing

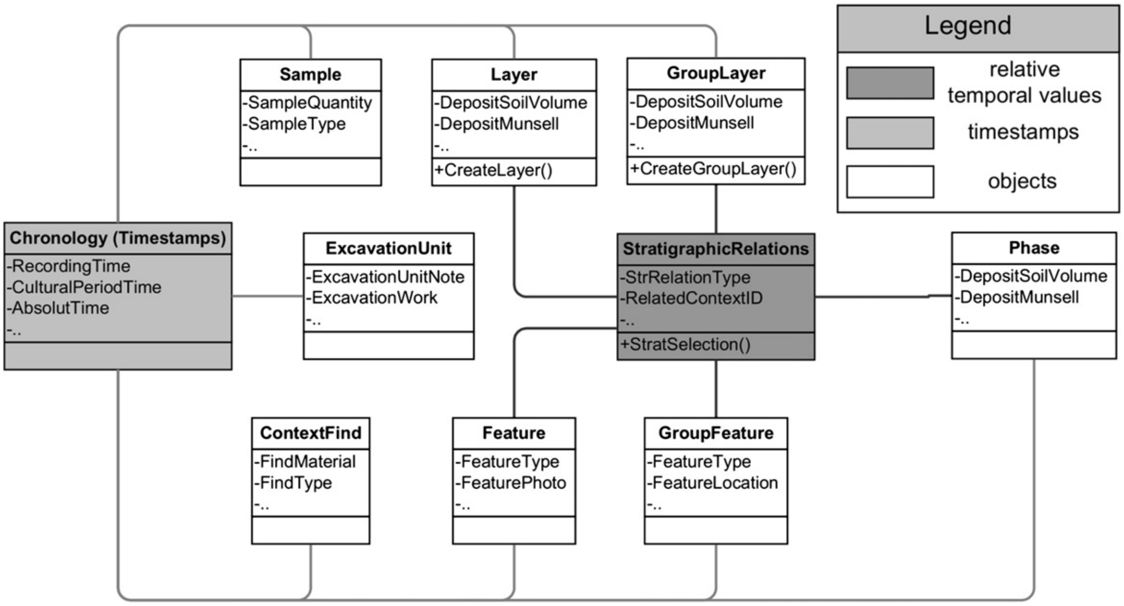


Fig. 5. Temporal class diagram.

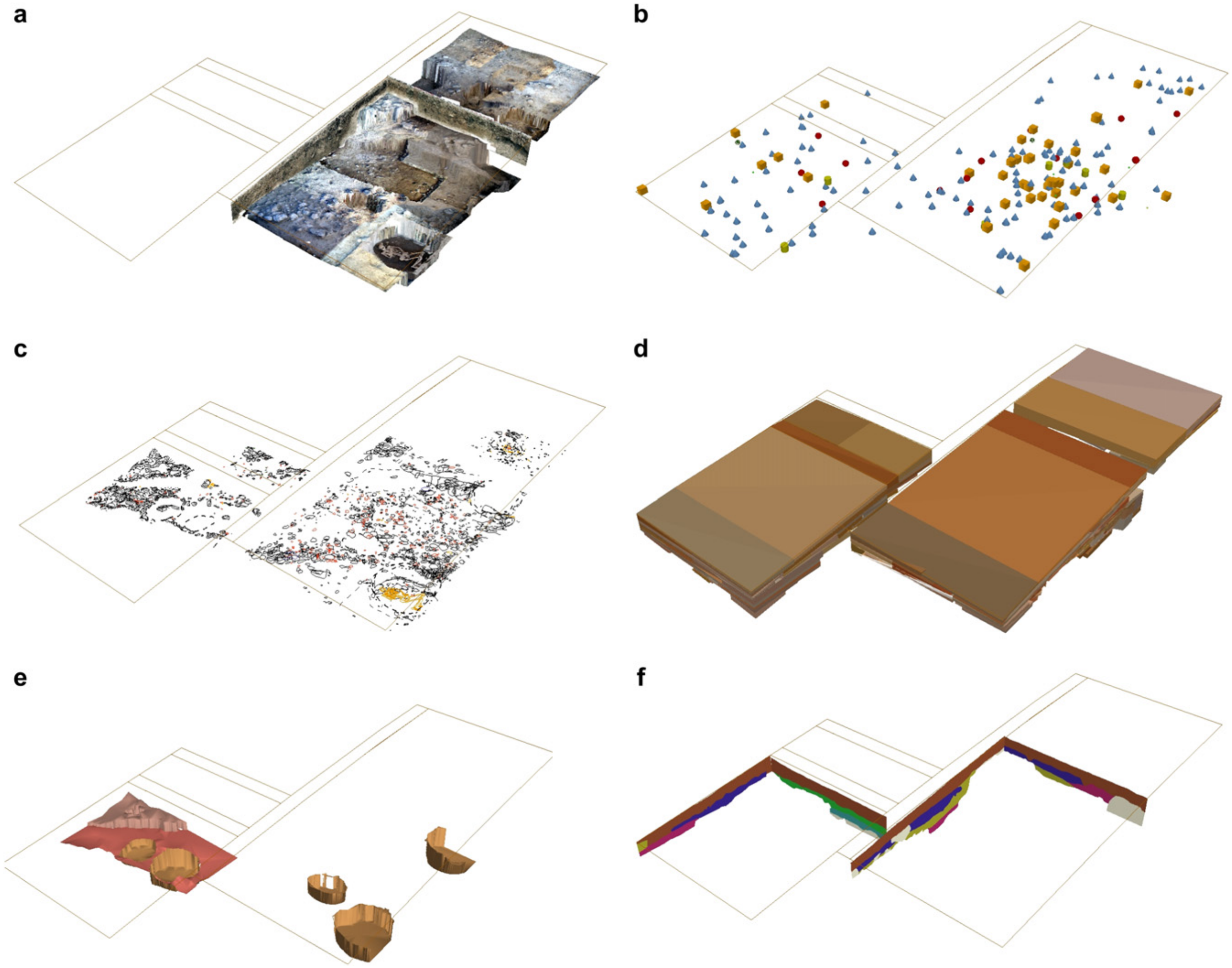


Fig. 6. Object representation in 3D. (a) Raster images of plans and sections, (b) finds and environmental samples, (c) drawings, (d) units, (e) architectural features, (f) digitized sections.

options, we feel that with the shift of archaeological recording and representation to 3D environments new forms for cartographic design and spatial communication should be explored and introduced (Fig. 8).

6. System functionality

The visualization of these elements in a GIS environment and the manipulation of the object-oriented relationships

Fig. 7. (a) Photo of unearthed door pivot, (b) photo draped over area DEM, (c) multipatch object created in Sketch Up from elevation TIN.

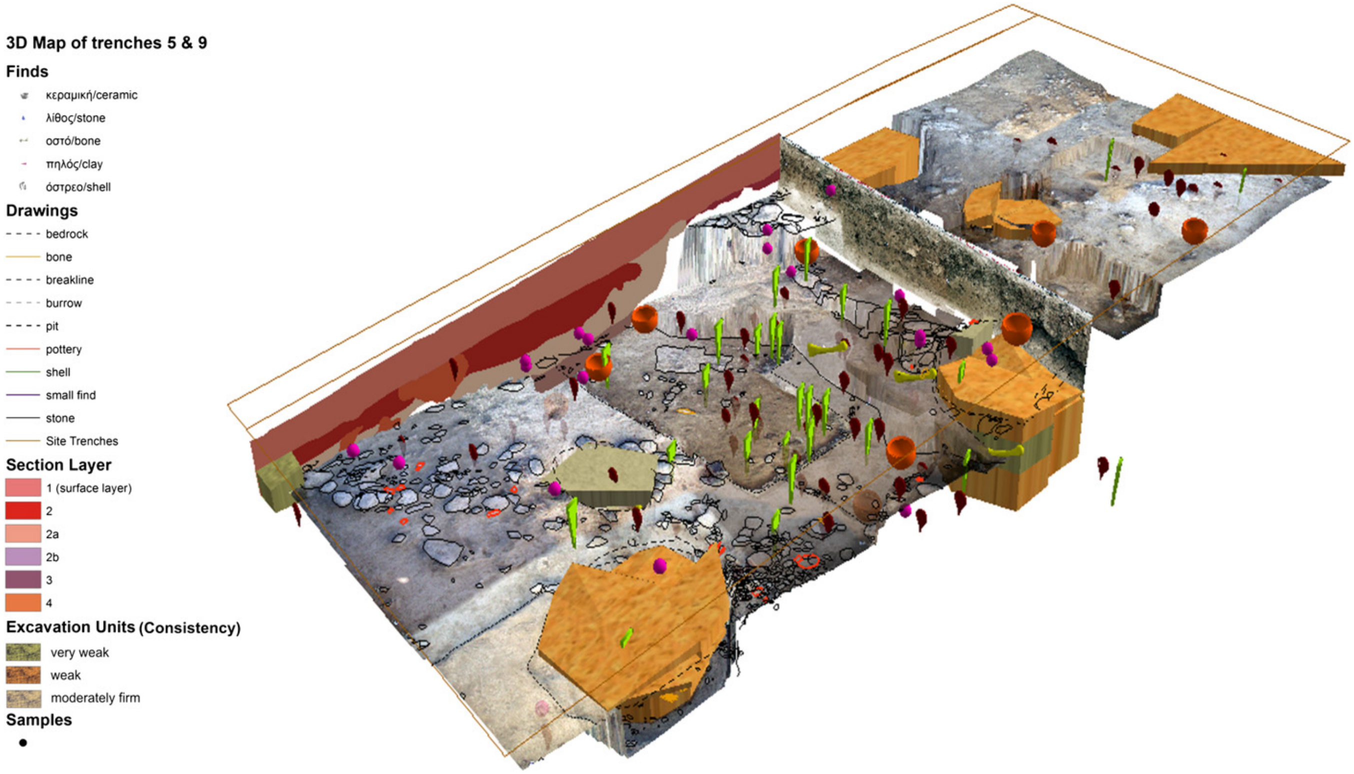


Fig. 8. Combination of trenches, excavation units, finds, drawings and photos with advanced symbology.

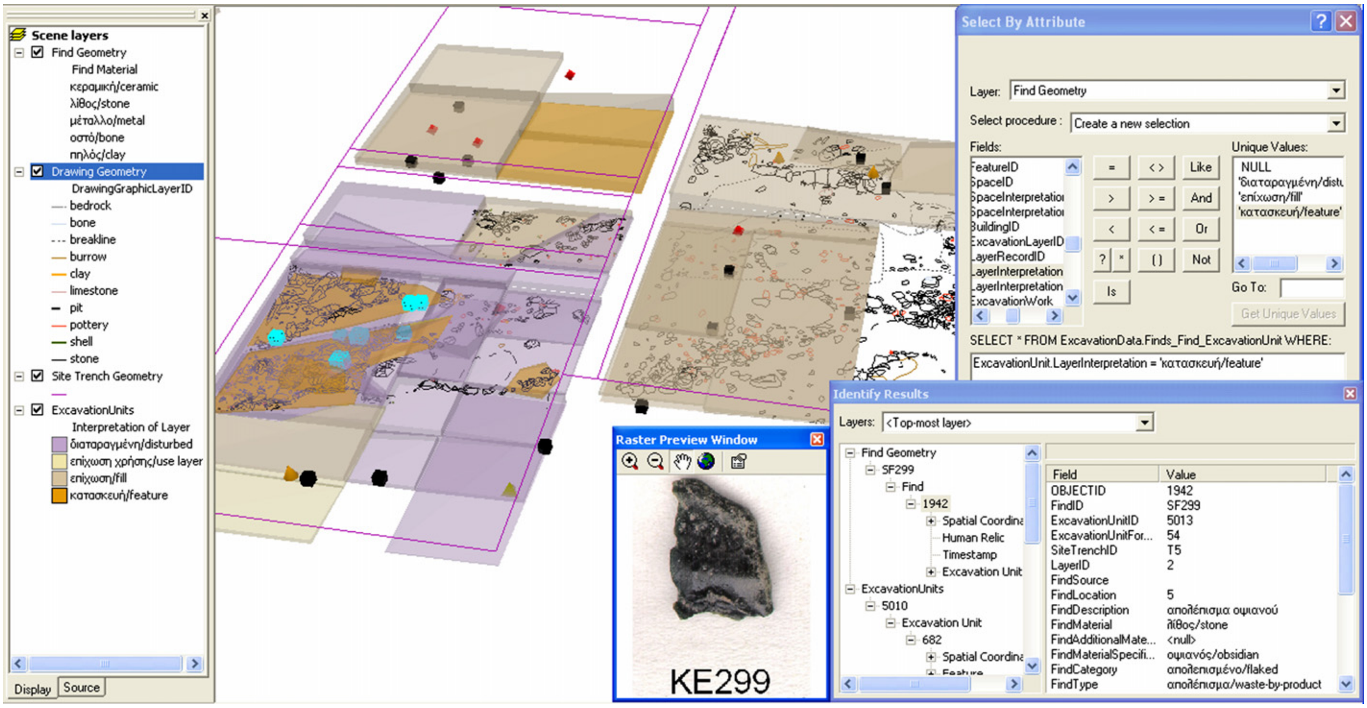
defined in the data model are possible through a range of existing and generally available tools. These tools enable the user to navigate through the data, re-establish the connection between objects and their contexts as well as reveal misunderstandings that occurred during fieldwork. Basic data exploration functionality offered by most GIS packages includes the identification of archaeological features, their selection and classification based on attribute data and the construction of more complex thematic queries (Conolly and Lake, 2006: 112–149) (Fig. 9).

6.1. Custom tools

Despite these existing options, the process of archaeological reasoning requires further functionality that is not present in most GIS software but can be implemented by various programming routines (e.g. Visual Basic, Arc Objects, C). For our purposes at Paliambela, we have developed three main tools that facilitate aspects of archaeological reasoning process and digital documentation.

First, for exploring features in 3D space, operations such as calculating distances or selecting objects based on 3D buffering can enhance the process of defining and understanding archaeological entities and their contexts. Following the example presented by Nigro et al. (2003), we have developed a 3D point-to-point distance tool that can be used to perform spatial queries on either single X, Y, Z records or multipoint entities (Fig. 10a,b). These queries can be restricted to a specific 3D search radius (e.g. within 3 m of a particular location), a direction (e.g. north-east of a particular location) or a vaguer spatial association (e.g. nearest to). By calculating global distance measurements between a set of points in 3D space, we are also able to compute the minimum, maximum, mean and total distance of a point (e.g. a find) in relation to all other points of a defined dataset. These measurements can form the basis for the implementation of spatial statistics. As shown in Fig. 10c, the application of a nearest neighbour analysis followed by a z significance test, can help in the indication of spatial patterning within a specified artefact population. More sophisticated statistics, can be performed within specialized software (SPSS, S-Plus, R) after these measurements are exported as a standalone table.

A second important aspect of spatial data exploration is the ability to perform and store user-defined sections, so as to give an idea of the vertical or horizontal stratigraphic layout of excavation units inside a trench. Drawing on previous experience from the RUNSECT program developed in the mid-1980s (Kotsakis, 1989) and using 3D geometry, a plane can be defined by the user anywhere in the site area. A programming routine computes the points of intersection between each excavation unit and the plane. Based on these points a 3D polygon, depicting the footprint of each excavation unit over the plane, is created and can be stored in the database. The aggregate of this process for all intersecting units provides an arbitrary, user-specified section through the site. Each of the resulting section polygons can then also be linked to the information of each excavation unit and participate in all its relationships within the data model (Fig. 11).



Layer: Find Geometry

Select procedure : Create a new selection

SELECT * FROM ExcavationData.Finds_Find_ExcavationUnit WHERE:

ExcavationUnit.LayerInterpretation = 'κατασκευή/feature'

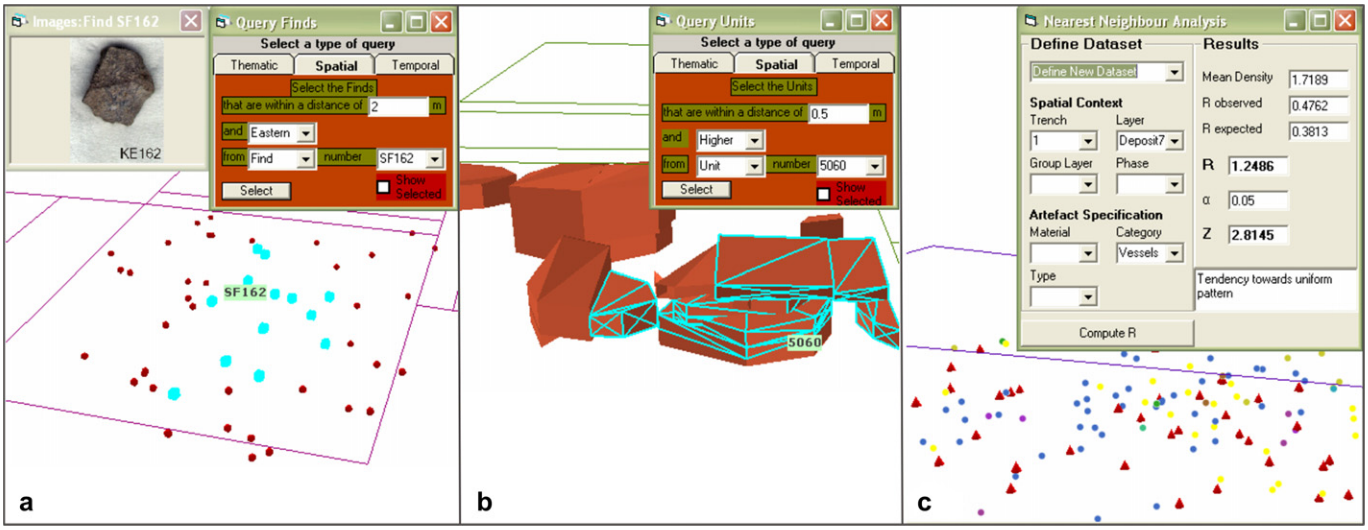
Layers: <Top-most layer>

Field	Value
OBJECTID	1942
FindID	SF299
ExcavationUnitID	5013
ExcavationUnitFor...	54
SiteTrenchID	T5
LayerID	2
FindSource	
FindLocation	5
FindDescription	απολέπισμα οψιανού
FindMaterial	λίθος/stone
FindAdditionalMate...	<null>
FindMaterialSpecifi...	οψιανός/obsidian
FindCategory	απολεπισμένο/flaked
FindType	απολέπισμα/waste-by-product

Fig. 9. Thematic data classification, thematic selection and identification of features.

Finally, to assist stratigraphic interpretation we have also implemented a third tool that draws on the UML data model classes and allows the user to aggregate them into higher level stratigraphic entities (see Section 4.2). This method is similar to the grouping process that often occurs in context-based recording in the field (e.g. where individual contexts are given grouping numbers). The creation of an aggregated object is followed by the summary of the interval or ratio-scale values (e.g. volume) of each constituent object, whereas nominal-scale values (e.g. soil texture) are summarized by the archaeologist after checking their presence ratio within the aggregated population. The stratigraphic relationships in which this object participates (i.e. Group Layer III is earlier than Group Layer IV) are defined by the archaeologist and registered in the related table. Additional temporal attributes such as creation date or cultural period classification can also be assigned at this stage (Fig. 12).

The 3D representation of deposit entities and the exploration of their stratigraphic relations in 3D space can be a lot more informative than a 2D stratigraphic sequence diagram (Harris Matrix) (Adams, 1992; Chadwick, 1998; Day et al., 2004). By visualizing simple temporal queries such as “*select*



Select the Finds that are within a distance of 2 m and Eastern from Find number SF162

Select the Units that are within a distance of 0.5 m and Higher from Unit number 5060

Define New Dataset

Spatial Context

Trench: 1

Layer: Deposit7

Group Layer:

Phase:

Artefact Specification

Material:

Category: Vessels

Type:

Mean Density: 1.7189

R observed: 0.4762

R expected: 0.3813

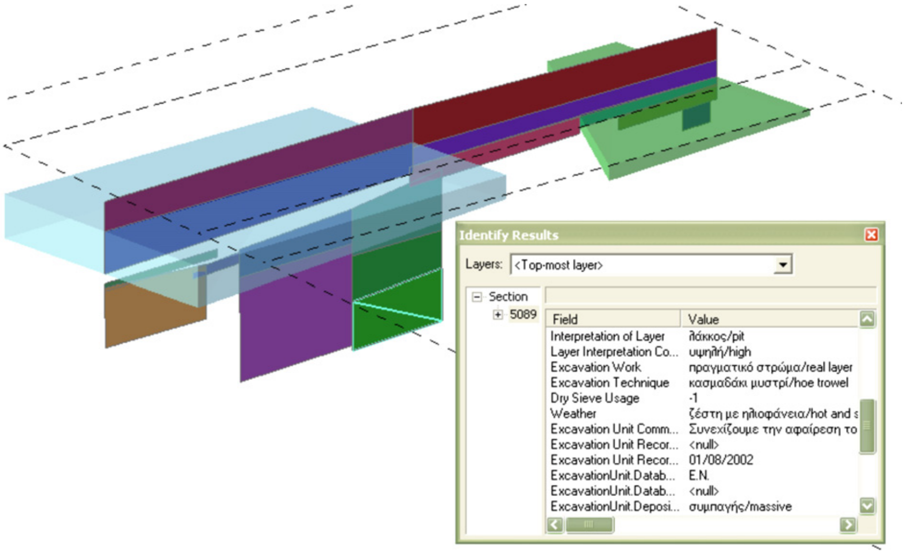
R: 1.2486

α: 0.05

Z: 2.8145

Tendency towards uniform pattern

Fig. 10. Data exploration in 3D space: (a) selection of finds by 3D distance, (b) selection of excavation units by 3D distance, (c) applied nearest neighbour analysis.



Field	Value
Interpretation of Layer	λάκκος/pit
Layer Interpretation Co...	υψηλή/high
Excavation Work	πραγματικό στρώμα/real layer
Excavation Technique	κασμαδάκι μυστρί/hoe trowel
Dry Sieve Usage	-1
Weather	ζέστη με ηλιοφάνεια/hot and s
Excavation Unit Comm...	Συνεχίζουμε την αφαίρεση το
Excavation Unit Recor...	<null>
Excavation Unit Recor...	01/08/2002
ExcavationUnit.Datab...	E.N.
ExcavationUnit.Datab...	<null>
ExcavationUnit.Deposi...	συμπαγής/massive

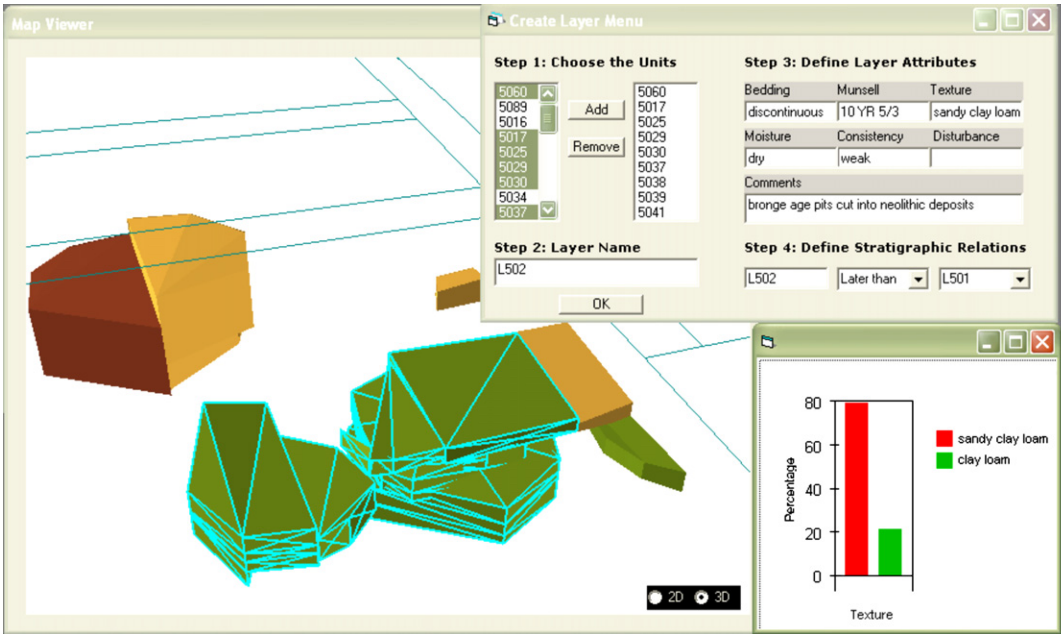
Fig. 11. Vertical section of trench 5. Two excavation units are shown as transparent.

the group layers directly related to group layer IV'', anomalies can be revealed by visual examination and relationships can be re-evaluated. However, the full depiction of a complex stratigraphic sequence in 3D space using actual deposit display needs to be further enhanced by innovative forms of symbology in order to be entirely effective.

7. Benefits from using GIS

Using digital recording forms for attribute data input and the aforementioned recording routines for the construction of the spatial features, almost 50% of the site's analog archive at Paliambela has already been digitized and linked to the related spatial representations (15 out of 29 trenches, 2500 out of ∼4000 excavation units, 4500 out of ∼4500 finds, 4000 out of ∼4000 samples, 25 out of ∼130 plans, 15 out of ∼300 features and 5 user-defined sections). All this information (vector datasets and attribute data tables) does not exceed 30 MB of disk memory (excluding, of course, all raster and grid files that are stored externally in system folders). As a result, the display of all this material can be handled effectively within the 3D viewing environment.

Field recording using this routine was given a final test during the excavation period of summer 2006 and resulted in having 75% of the material digitized by the end of fieldwork. The digital recording process of six 5 × 5 trenches during 6 weeks



Step 1: Choose the Units

5060
5089
5016
5017
5025
5029
5030
5034
5037

5060
5017
5025
5029
5030
5037
5038
5039
5041

Step 2: Layer Name

L502

Step 3: Define Layer Attributes

Bedding	Munsell	Texture
discontinuous	10 YR 5/3	sandy clay loam
Moisture	**Consistency**	**Disturbance**
dry	weak	

Comments: bronge age pits cut into neolithic deposits

Step 4: Define Stratigraphic Relations

L502 Later than L501

Fig. 12. Grouping excavation units into a higher-level stratigraphic entity. The bottom right chart allows the user to decide how to aggregate nominal-scale variables such as soil texture.

of excavation was based on the use of a single total station, a digital camera, two laptops and a desktop computer. Apart from the authors, one surveyor and two students (one for attribute data input and another for plan vectorization) were engaged in the recording process full time during the whole period.

The unification of the recording workflow on a single GIS platform has allowed the rapid and cost-effective creation of the excavation's digital archive. The representation of the excavation features in 3D space and the ability for the archaeologist to explore relationships and visualize his or her queries overturns the view of the excavation archive as static and inaccessible. Although accessing the data is admittedly difficult for archaeologists inexperienced with GIS technology, a custom-interface is under development, so that the exploration of data can be performed without necessarily having the GIS expert present. Finally, the usage of GIS ISO 19115 allows the dissemination of the data through the internet on the basis of XML database schema and related export facilities.

8. Discussion

To conclude, GIS is very close to becoming a powerful and wholly effective tool for 3D intra-site documentation and analysis. The model developed for Paliambela Kolindros can be broadly applied to other sites that present similarities in excavation methodology. The systematic exploration of archaeological reasoning processes within the domains of ontology, visualization and time can reveal new opportunities for the organization, analysis and representation of archaeological data in GIS environments. Our focus here has been on providing a solution for contemporary intra-site archaeological research, after careful consideration of the excavation process and in full view of current computational possibilities. In this sense, the proposed workflow allows the recording of archaeological observation in a digital GIS environment, which can support tools for the exploration of archaeological information and provide the ability for further data structuring in a data-led synthetic manner. We also hope it will promote further discussion and development in both the commercial and Open Source sectors.

Acknowledgements

The work presented is funded by the EU and the Greek Ministry of Development (Operational Programme "*Competitiveness*", Priority Axis 8: *Human resources*, Measure 8.3: *Human resources in Research & Technology*). Development support is provided by VOYAGER Mobile Technologies™. We would like to acknowledge Prof. Yiannis Manolopoulos for his guidance in spatiotemporal database theory. Also, Dr Andy Bevan for his active participation in the project and his valuable comments on previous versions of this paper.

References

Adams, M., 1992. Stratigraphy after Harris: some questions. In: Steane, K. (Ed.), Interpretation of Stratigraphy: a Review of the Art. Proceedings of the 1st Stratigraphy Conference, Lincoln. City of Lincoln Archaeology Unit, Lincoln, pp. 13–16.

Apel, M., 2004. A 3d geoscience information system framework. Freiberg University, Doctoral thesis. <http://www.gocad.org/www/people/files/thesis_marcus_apel.pdf>.

Arroyo-Bishop, D., Lantada Zarzosa, M.T., 1995. To be or not to be: will an object-space-time GIS/AIS become a scientific reality or end up an archaeological entity? In: Lock, G.R., Stancic, Z. (Eds.), Archaeology and Geographic Information Systems: A European Perspective. Taylor & Francis, London, pp. 43–53.

Bailey, G.N., 1983. Concepts of time in quaternary prehistory. Annual Review of Anthropology 12, 165–192.

Barceló, J.A., De Castro, O., Traver, D., Vicente, O., 2003. A 3D model of an archaeological excavation. In: Doerr, M., Sarris, A. (Eds.), The Digital Heritage of Archaeology. Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 30th Conference, Heraklion, Crete, April 2002. Hellenic Ministry of Culture, Greece, pp. 85–87.

Barceló, J.A., Vicente, O., 2004. Some problems in archaeological excavation 3D modelling. In: Ausserer, K.F., Borner, W., Goriany, M., Karlhuber-Vockl, L. (Eds.), Enter the Past: The E-way into the Four Dimensions of Cultural Heritage. CAA2003, BAR International Series 1227. Archaeopress, Oxford, pp. 400–404.

Bezzi, A., Bezzi, L., Francisci, D., Gietl, R., 2006. L'utilizzo di voxel in campo archeologico, Geomatic workbooks 6. <http://www.arc-team.com/Upload/Geom_Workbooks6_voxel_archeologia_it.pdf>.

Castleford, J., 1992. Archaeology, GIS and the time dimension: an overview. In: Lock, G., Moffett, J. (Eds.), Computer Applications and Quantitative Methods in Archaeology 1991. BAR International Series S577. Tempus Reparatum, Oxford, pp. 95–106.

Cattani, M., Fiorini, A., Rondelli, B., 2004. Computer applications for a reconstruction of archaeological stratigraphy as a predictive model in urban and territorial contexts. In: Ausserer, K.F., Borner, W., Goriany, M., Karlhuber-Vockl, L. (Eds.), Enter the Past: The E-way into the Four Dimensions of Cultural Heritage. CAA2003, BAR International Series 1227. Archaeopress, Oxford, pp. 299–303.

Chadwick, A., 1998. Archaeology at the Edge of Chaos: Further Towards Reflexive Excavation Methodologies, Assemblage 3. <http://www.shef.ac.uk/~assem/3/3chad.htm>.

Clark, P., 2000. Post-excavation analysis: moving from the context to the phase. In: Roskams, S. (Ed.), Interpreting Stratigraphy. Site Evaluation Recording Procedures and Stratigraphic Analysis. BAR International Series 910, Oxford, pp. 157–159.

Clarke, A., Fulford, M., Rains, M., 2003. Nothing to hide – online database publication and the Silchester Town Life Project. CAA 2002. In: Doerr, M., Sarris, A. (Eds.), The Digital Heritage of Archaeology. Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 30th Conference, Heraklion, Crete, April 2002. Hellenic Ministry of Culture, Greece, pp. 401–404.

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

Constantinidis, D., in press. Time to look for a temporal GIS, in: The World is in Your Eyes: Computer Applications and Quantitative Methods in Archaeology 2005, Tomar, 21–24 March 2005.

Cripps, P., Greenhalgh, A., Fellows, D., May, K., Robinson, D., 2004. Ontological Modelling of the work of the Centre for Archaeology. <http://cidoc.ics.forth.gr/docs/Ontological_Modelling_Project_Report_%20Sep2004.pdf>.

Crofts, N., Doerr, M., Gill, T., Stead, S., Stiff, M., 2005. Definition of the CIDOC Conceptual Reference Model, Version 4.2, ICOM/CIDOC CRM Special Interest Group. <http://cidoc.ics.forth.gr/docs/cidoc_crm_version_4.2.pdf>.

D'Andrea, A., 2003. Analisi spaziali intra-site. Soluzioni GIS per lo scavo archeologico. Archeologia e Calcolatori 14, 329–335.

Day, W., Cosmas, J., Ryan, N., Vereenooghe, T., 2004. Integrated 3D and Harris matrix data entry, query and visualisation tools, in: 5th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage - VAST2004, December 2004, Brussels.

Dennis, A., Haley Wixom, B., Tegarden, D., 2001. Systems Analysis and Design: an Object-Oriented Approach with UML. John Wiley & Sons, Inc, New York.

Doerr, M., 2003. The CIDOC CRM – An ontological approach to semantic interoperability of metadata. AI Magazine 24 (3). <http://www.ics.forth.gr/isl/publications/paperlink/Doerr_V2.pdf>.

Dykes, J., MacEachren, A.M., Kraak, M.-J. (Eds.), 2005. Exploring Geovisualization. Elsevier, Amsterdam.

ESRI, 1998. ESRI Shapefile Technical Description. White Paper. Environmental Systems Research Institute, Inc., Redlands, CA. <http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf>, pp. 1–34.

Gosden, C., 1994. Social Being and Time. Blackwell, Cambridge.

Hadzilakos, T., Stoumbou, P.M., 1996. Conceptual data modelling for prehistoric excavation documentation. In: Kamermans, H., Fennema, K. (Eds.), Interfacing the Past: Computer Applications and Quantitative Methods in Archaeology 1995. University of Leiden, Leiden, pp. 21–30.

Herzog, I., 2004. Group and conquer: a method for displaying large stratigraphic data sets. In: Ausserer, K.F., Borner, W., Goriany, M., Karlhuber-Vockl, L. (Eds.), Enter the Past: The E-way into the Four Dimensions of Cultural Heritage. CAA 2003. BAR International Series 1227. Archeopress, pp. 423–426.

Hodder, I., 1999. The Archaeological Process: An Introduction. Blackwell, Oxford.

Jarroush, J., Even-Tzur, G., 2004. Constructive Solid Geometry as the Basis of 3D Future Cadastre, FIG Working Week 2004. Greece, Athens. <http://www.fig.net/pub/athens/papers/ts25/TS25_3_Jarroush_EvenTzur.pdf>. May 2004.

Jones, A., 2002. Archaeological Theory and Scientific Practice. Cambridge University Press, Cambridge.

Katsianis, M., Tsipidis, S., Kotsakis, K., Koussoulakou, A., Manolopoulos, Y., 2006. Integrating excavation recording, data management and object representation through GIS. In: International Congress ‘‘Cultural Heritage and New Technologies’’ Workshop 10 – Archäologie Und Computer, 7–10/11/2005, Vienna.

Kotsakis, K., 1989. RUNSECT: a computer program for the analysis of excavation data. Journal of Field Archaeology 16, 369–375.

Kotsakis, K., Katsianis, M., Tsipidis, S., in press. Digital Recording of Archaeological Data Using GIS in Paliambela, Kolindros. Archaeological Work in Macedonia and Thrace Annual Conference 19, Thessaloniki, Greece 2006 (in Greek).

Koussoulakou, A., Stylianidis, E., 1999. The use of GIS for the visual exploration of archaeological spatiotemporal data. Cartography and GIS 26 (2), 152–160.

Kvamme, K.L., 1999. Recent directions and developments in geographical information systems. Journal of Archaeological Research 7 (2), 164–167.

Lock, G., 1995. Archaeological computing, archaeological theory and moves towards contextualism. In: Huggett, J., Ryan, N. (Eds.), Computer Applications and Quantitative Methods in Archaeology. BAR International Series 600. Tempus Reparatum, Oxford, pp. 13–18.

Lock, G., 2003. Using Computers in Archaeology: Towards Virtual Pasts. Routledge, London and New York.

Losier, L.-M., Pouliot, J., Fortin, M., 2007. 3D geometrical modeling of excavation units at the archaeological site of Tell ‘Acharneh (Syria). Journal of Archaeological Science 34, 272–288.

Lucas, G., 2005. The Archaeology of Time. Routledge, Abingdon.

Madsen, T., 2003. ArchaeoInfo: An Object Oriented Information System for Archaeological Excavations, Paper presented at the CAA 2003: Enter the Past: The E-way into the Four Dimensions of Cultural Heritage. Austria, April 2003, Vienna.

Nigro, J.D., Ungar, P.S., De Ruiter, D.J., Berger, L.R., 2003. Developing a Geographic Information System (GIS) for mapping and analysing fossil deposits at Swartkrans, Gauteng Province, South Africa. Journal of Archaeological Science 30, 317–324.

Olivier, L., 2004. The past of the present. Archaeological memory and time. Archaeological Dialogues 10 (2), 204–213.

Patias, P., Stylianidis, E., Tsioukas, V., Gemenetzis, D., 2005. Rapid Photogrammetric Survey and GIS Documentation of Pre-historic Excavation Sites. CIPA-WG 5.

Perez, C.A.G., 2002. Sistemas De Información para Arqueología: Teoría, Metodoloxía y Technoloxías. BAR International Series 1015. Archaeopress, Oxford.

Powlesland, D., Clemence, H., Lyall, J., 1998. West Heslerton: WEB-CD. The application of HTML and WEB tools for creating a distributed excavation archive in the form of a WEB-CD. Internet Archaeology 5 (Autumn/Winter).

Roskams, S.P., 2001. Excavation (Cambridge Manuals in Archaeology). Cambridge University Press, Cambridge.

Sellis, T., Koubarakis, M., Frank, A., Grumbach, S., Gueting, R.H., Jensen, C., Lorentzos, N., Manolopoulos, Y., Nardelli, E., Pernici, B., Schek, H.J., Scholl, M., Theodoulidis, B., Tryfona, N. (Eds.), 2003. Spatiotemporal Databases: the Chorochronos Approach. Lecture Notes in Computer Science, Vol. 2520. Springer Verlag.

Shanks, M., Tilley, C., 1987. Social Theory and Archaeology. Polity Press, Cambridge.

Stoter, J.E., Zlatanova, S., 2003a. 3D GIS, where are we standing? in: Proceedings of the ISPRS WG II/6, IV/1 and IV/2 Joint Workshop on 'Spatial, Temporal and Multi-dimensional Data Modelling and Analysis'. ISPRS, London.

Stoter, J.E., Zlatanova, S., 2003b. Visualising and editing of 3D objects organised in a DBMS. In: Proceedings of the EuroSDR Commission 5 Workshop on Visualisation and Rendering. EuroSDR, Cambridge.

Tiede, D., Blaschke, T., 2005. A two-way workflow for integrating CAD, 3D visualization and spatial analysis in a GIS environment. In: Buhmann, E., Paar, P., Bishop, I., Lange, E. (Eds.), Trends in Real-Time Landscape Visualization and Participation. Proceedings at Anhalt University of Applied Sciences 2005. Wichmann Verlag, Heidelberg, pp. 77–87. <http://www.masterla.de/conf/pdf/conf2005/23tiede_c.pdf>.

Tsipidis, S., Koussoulakou, A., Kotsakis, K., 2005. 3D GIS Visualization of Archaeological Excavation Data, Poster presentation at the International Cartographic Conference (ICC 2005) 9–16/7/2005, La Coruña. <http://www.cartesia.org/geodoc/icc2005/pdf/poster/TEMA26/SPYROS%20TSIPIDIS.pdf>.

Wheatley, D., Gillings, M., 2002. Spatial Technology and Archaeology. The Archaeological Applications of GIS. Taylor & Francis, London and New York.

Zlatanova, S., Rahman, A.A., Pilouk, M., 2002. Trends in 3D GIS development. Journal of Geospatial Engineering 4 (2), 1–10.

Zhukovsky, M., 2002. Handling digital 3-D record of archaeological excavation data. In: Burenhult, G. (Ed.), Archaeological Informatics: Pushing the Envelope. CAA2001, BAR International Series 1016. Archaeopress, Oxford, pp. 431–438.