The Tell el-Daba Archaeological Information System: Adding the Fourth Dimension to Legacy Datasets of Long-Term Excavations (A Puzzle in 4D)

Matthias Kucera[1] – *Wolfgang Neubauer*[2] – *Sandra Müller*[3] – *Milena Novak* – *Juan Torrejón-Valdelomar*[4] – *Mario Wallner*[5] – *Alois Hinterleitner*[6] – *Andreas Lenzhofer*[7] – *Christoph Traxler*[8]

Abstract: Archaeological research relies on the documentation and analysis of archaeological entities in space and time, i.e. the stratigraphic ordering of these units, resulting in a stratigraphic sequence. A GIS-based Archaeological Information System (AIS) organises archaeological entities and associated attributable information according to its specific three-dimensional geographical position based on the framework provided by a Geographical Information System (GIS). To compile a stratigraphic sequence of these entities located in space, the GIS-based AIS must be extended by a fourth dimension – time. The paper presents the associated extension of ArcGIS (ESRI) by a stratigraphic sequence composer with an integrated interval-based time model as the basic digital environment for spatio-temporal analysis of archaeological excavation datasets. The long-term excavation at Tell el-Daba, Egypt was chosen as a case study to evaluate the applicability of various digital analysis tools using a geo-referenced 4D AIS on non-digital and incomplete excavation datasets. As most existing archaeological excavation datasets are based upon long-term inconsistent and analogue data, it is crucial to integrate and handle such data to ensure their accessibility for state-of-the-art archaeological spatio-temporal data analysis.

Keywords: GIS-based archaeological information system (AIS), 4D GIS, spatio-temporal analysis, legacy dataset, comparability, Allen‘s interval algebra, stratigraphic sequencing tool

Most archaeological datasets rely on legacy data recorded throughout previous decades and even centuries. In fact, most archaeological data and information are based on long-term excavations and surveys that include inconsistencies due to evolving documentation systems and missing data due to arbitrary excavation. Especially since the introduction of the principles of archaeological stratigraphy in 1979[9] archaeological methodology has seen basic changes in the paradigm, resulting in major developments in applied documentation techniques and basic theoretical concepts enforced by the advent of geographical information systems (GIS).[10]

1 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), matthias.kucera@archpro.lbg.ac.at.

2 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), wolfgang.neubauer@archpro.lbg.ac.at.

3 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), sandra.maria.mueller@univie.ac.at.

4 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), jtv@7reasons.net.

5 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), mario.wallner@archpro.lbg.ac.at.

6 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), alois.hinterleitner@archpro.lbg.ac.at.

7 VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, lenzhofer@vrvis.at.

8 VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, traxler@vrvis.at.

9 Harris 1989.

10 Neubauer 2004.

Considering the fact that archaeological excavation results are always interpretative and depend on the applied methods,[11] the issue of intra-site and inter-site comparability of results based on the various methodological approaches applied becomes prevalent. Especially the aspects of intra-site integration of stratigraphic sequences and their inter-site comparison are of vital importance. With respect to the spatial and temporal properties of every archaeological entity an archaeological information system (AIS) for the organisation, display and analysis must be GIS-based[12] and extended to 4D.[13]

The digitisation of analogue excavation archives is crucial for comparability with new digital datasets achieved through state-of-the-art methodologies (e.g. stratigraphic excavations, digital recording techniques, geo-archaeological and morphological sampling). Redundancy is increased regarding the preservation of the data. To increase comparability and reproducibility of results a standardised workflow for the digitisation, interpretation and spatio-temporal analysis of the data is necessary. The aim of the project ‘A Puzzle in 4D’ is to develop and apply workflows and techniques to digitally preserve, archive and interpret legacy data using the example of the excavations at Tell el-Daba (TD).[14] Furthermore the possibility of reconstructing undocumented and missing information will be examined according to a procedure best described as ‘reverse excavating’. Reconstruction of the workflow of the original excavation and translation into a stratigraphic sequence datasets can be completed and the reliability of given datasets evaluated. Major scientific tasks are the digitisation of the Tell el-Daba legacy datasets, metadata and semantic enrichment, the development of strategies for data archiving and open source access according to international standards, the development of a 4D AIS, virtual reconstruction, visualisation and dissemination.

The development of a GIS-based 4D AIS will secure comparability of the Tell el-Daba legacy datasets in accordance with stratigraphic theory and methodology, a task mainly undertaken by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro). Best routines for every task will be evaluated and standardised. We will show that the AIS will enhance and simplify further archaeological interpretation. Respective results will be reproducible in respect to the confirmability of the origin of the archaeological information.

Within this paper we present: (1) the basic applied principles and rules for the segmentation of space into stratigraphic units (SU), resulting in spatio-temporal relations displayed by a stratigraphic sequence; (2) the basic design and components of a GIS-based 4D AIS recently developed and (3) an initial suggestion for a standardised workflow for digital segmentation and archaeological interpretation optimised for the Tell el-Daba dataset.

The Case Study of Tell el-Daba

Tell el-Daba is an archaeological site located approximately 150km northeast of Cairo in the fertile Nile delta and has revealed archaeological evidence from the 12th to 18th dynasties (early 2nd millennium BC).[15] During the 15th dynasty it was the capital city of the Hyksos. The area of the ancient town covers about 2.5km^2. Since 1966 excavations were conducted by the Austrian Archaeological Institute (ÖAI) under the direction of Manfred Bietak. Around 50 years of active fieldwork campaigns have been carried out, resulting in an enormous amount of field protocols, drawings, photographs and prospection survey data. The excavations uncovered mainly residential buildings, tombs and temples illustrating the contacts of a wealthy society to many parts of the eastern Mediterranean. The site is also famous for Minoan style wall paintings reconstructed

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[11] Kucera – Löcker 2007.

[12] Arroyo-Bishop – Lantada Zarzosa 1995.

[13] DeRoo et al. 2014.

[14] Aspöck et al. 2015; Aspöck et al., this volume.

[15] Bietak 1970; Bietak 1975; Bietak 1991; Bietak 1996; Bietak 2010; Bietak et al. 2001; Bietak et al. 2007; Kopetzky 2010. For a summary see Aspöck et al., this volume.

out of thousands of fragments. Reconstructions show scenes with bulls and bull-leapers, indicating a unique connection to Minoan culture. The excavations have been carried out with a mixed methodology of excavating in spits biased by observable artificial surfaces such as walls and floors.

Since the start of excavation, the applied methodology stayed the same to ensure consistency in the dataset. Documentation methodology changed however in 1996 with the introduction of the so-called locus system at Tell el-Daba. In many instances a locus corresponds to the definition of a stratigraphic unit, but generally what a locus is defined individually at each excavation. Further changes in the documentation methodology took place as part of technological advances in the field, as increasingly digital documentation methods have been used.

Excavations at Tell el-Daba have taken place in five areas (Ezbet Helmi (H/I-VI), Ezet Rushdi (R/I-IV), Catana (E/I), Tell (A/N+A/I-V), Feld (F/I-II)), which are subdivided into quadratic trenches (squares) of usual sizes of 10×10m or 15×15m. The squares were separated by bars of 1m width for the purpose of documentation of cross-sections. Each square was excavated in spits, resulting in a dataset which consists mainly of a handwritten record (including sketches), drawings (levels, details and cross-sections of scales 1:50, 1:20 and 1:10) and photographic documentation (B&W, RGB and slides). The main observed archaeological structures have been also interpretatively drawn in a generalised map (ink drawing) and partly digitised with AutoCAD (Intergraph). During the first campaigns a relative grid, which was geographically referenced and embedded within the global WGS84 coordinate system throughout a geodetic survey in 2008, was used for positioning.

Fig. 1 Situation at the excavations in TD in 1979. One-metre-wide bars separate the squares (15×15m) of area F/I (OREA archive)

For the development and testing of an AIS, which had to be optimised for digitisation, segmentation and analysis of the Tell el-Daba dataset, a subset of the data was chosen. Area F/I has already been analysed and interpreted archaeologically to allow comparison of the newly gained results with the existing archaeological interpretations. Archaeological structures documented in the respective area date from the first half of the 15th Dynasty (1650/40–1530 BC) to the late 12th Dynasty (1980/70–1800/1790 BC).[16]

In the uppermost levels of the area a temple was found dedicated to stratum a/2 (first half of the 15th Dynasty) followed by a villa belonging to stratum b (middle of the 13th to the end of the 12th Dynasty). Due to different utilisation phases of the villa stratum b was subdivided into b/3 to b/1. Within stratum b offering pits were also documented.[17] At a deeper level the ruin of a huge building, most likely a palace or villa from stratum c (beginning of the 13th to the end of the 12th Dynasty) was found as well as the palace/villa itself, belonging to stratum d/1 (early 13th to late

[16] See Aspöck et al., this volume, table 1.

[17] Müller 2002.

Fig. 2 Overview of square j/21 (level 3), area F/I in 1979 (OREA archive)

12th Dynasty).[18] Like the younger villa this building was subdivided into two utilisation phases d/1.1 and d/1.2 and respective tombs.[19] An earlier level yielded the Mittelsaalhaus belonging to stratum d/2 (early 13th to late 12th Dynasty) and including the workmen village[20] of stratum e, which dates to the 12th Dynasty. The mentioned strata are linked to the superordinate Tell el-Daba phases E/2 to N/1–3,[21] The temporal model of the described sequence of strata related to archaeological phases was the basis for the subsequent temporal analysis.

For detailed analysis a single trench (square j/21) was chosen to represent most types of observed archaeological features and structures.

For further analysis several specific levels of 40 additional squares displaying the palace and surrounding infrastructure of strata d/1 were added to the subset. The legacy dataset includes

[18] Eigner 1985.
[19] Schiestl 2009.
[20] Czerny 1999.
[21] Bietak 2013/2014.

analogue data (photographs, slides, cross section drawings, level drawings, detail drawings, field protocols, overview maps and topographical maps) and digital data (CAD technical plans, satellite imagery and topographical data). All these data were taken into account for developing a standardised digitisation and segmentation procedure[22].

Basic Principles of Segmentation

The first step within a comprehensive digitisation process was to transfer the various data sources, i.e. photographs, maps, sketches, lists, notebooks etc., into appropriate digital formats for further use in the GIS-based AIS.

The extraction of the relevant archaeological entities or SU from analogue or digitised excavation maps was based on digitisation using basic GIS functionality. Every SU, i.e. deposits and surfaces,[23] was characterised by its geographic position and extent. Surfaces were defined by their immaterial topography, whereas deposits bear material components such as artefacts, composition, texture etc.

Deposits and surfaces can be described further based on their spatial and temporal relations. From the analysis of spatial relations, i.e. superposition, a basic stratigraphic sequence according to the principles of archaeological stratigraphy[24] was derived. This sequence must be refined based on the temporal relations of all units. Since every archaeological entity could be defined temporally as a time span or interval rather than a point in time or event, a temporal analysis of the dataset must be carried out based on time intervals, advancing the event-based concept of simple temporal relations (earlier, later and contemporary). For this reason interval algebra as suggested by Allen[25] was introduced, as also recently shown by Drap et al.[26] As archaeological stratigraphy is based on 4D entities, it deals first of all with the analysis of spatio-temporal relations of archaeological stratigraphic units to derive the formation of the respective stratification. Only spatio-temporal analysis is capable of illustrating the changes of an archaeological site or landscape. For defining temporal relation a physical superposition (i.e. the entities may not be in direct physical contact) of SU is not necessary. This approach is similar to the monitoring of various processes that change the attributes or shape of volumes in time, e.g. earth slides, flooding and mining.[27]

GIS-Based AIS

The main focus of the research and development done by the LBI ArchPro was the design and implementation of the different components of a GIS-based AIS. Because of the geographical character of archaeological excavation information, the appropriate framework is provided by a GIS. Based on the LBI ArchPro's long-term experience of the application of ArcGIS (ESRI) for the interpretation and analysis of archaeological data and also with respect to basic compatibility with other software, ArcGIS Desktop 10.2 was chosen. In contrary to CAD software a GIS

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22 The term 'digitisation' could be firstly used for transferring analogue into digital data. In this case a 1:1 projection of the illustrated information has to be achieved. Secondly it also describes the process of generalising this information e.g. if a drawing of a pit is reduced to its outline in drawing a polygon around it. This can also be called vectorisation of selected parts of the data. If this is the case, the digitisation results in the segmentation of an area or space.

23 Neubauer 2007; Traxler – Neubauer 2008.

24 Harris 1989.

25 Allen 1986.

26 Drap et al. 2017.

27 Kurte – Durbha 2016.

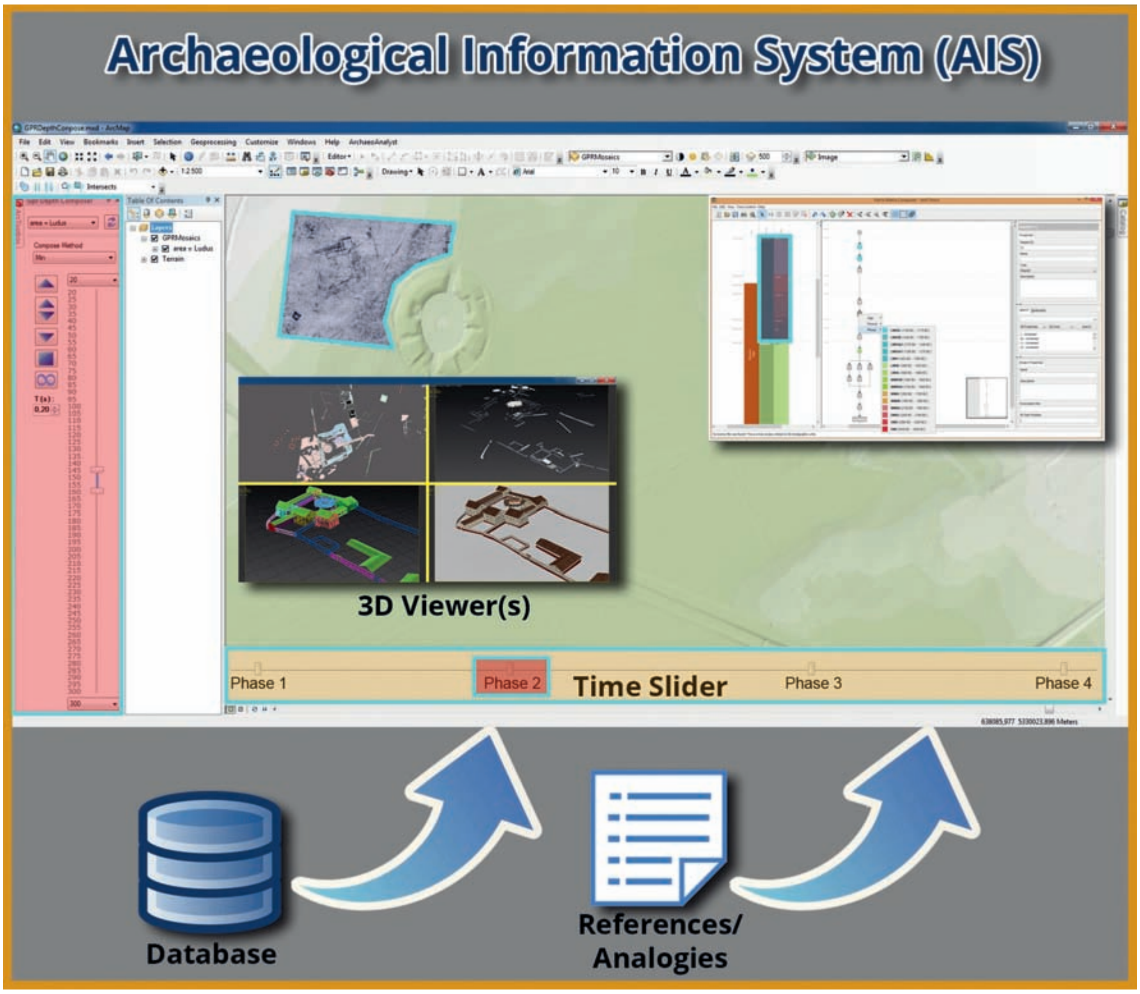

Fig. 3 Basic structure of a GIS-based AIS. It combines spatial and temporal information stored in a Geodatabase. Display, analysis and interpretation of the datasets are done within a GIS environment (LBI ArchPro)

is also capable of dealing with various types of information, e.g. information based on raster datasets, feature classes but also textual information. It is the most appropriate environment to segment space and correlate the generated areas or volumes with embedded archaeological information. A GIS provides an enormous set of various spatial analysis and data query tools. It is perfectly suited to analyse and display the spatial superposition of archaeological entities. For the digitisation and interpretation of 2D based information, e.g. drawings, photographs and maps, ArcMAP 10.2 was used, whereas for 3D visualisation ArcSCENE 10.2 proved to be perfectly suited for the Tell el-Daba dataset. Although initially a separate 3D viewer had been developed on the basis of true 3D, the 2.5D representation capabilities of ArcSCENE were sufficient. As 3D objects were derived from a few cross-sections and level drawings, the reconstructed geometry was very simple, and a 3D viewer was unnecessary. On the contrary datasets based on recent 3D data capturing techniques (e.g. image-based modelling[28] and terrestrial laser scanning[29]) bear more complex 3D geometry. A voxel-based approach for archaeological biased segmentation of space and further temporal analysis of geospatial processes is preferable.[30]

28 Doneus et al. 2011.
29 Doneus – Neubauer 2005; Neubauer 2007.
30 Jjumba – Dragićević 2016.

For temporal interpretation and display of SUs a stratigraphic sequencing tool had to be integrated into the AIS. For this purpose, the Harris Matrix Composer (HMC) had to be modified according to the specific demands of an interval-based temporal interpretation of the data. The first version of the HMC had been developed and released in 2007 (HMC V2.0b) to display the spatial superposition of SUs.[31] This early version provided the possibility for periodisation of groups of SUs but without a consistent temporal model.[32] To meet this requirement, the HMC was modified, and an interval-based time model was integrated, resulting in HMC+. For a spatio-temporal analysis of the dataset in the AIS the stratigraphic sequencer HMC+ was interfaced to ArcGIS. Currently the functionality is being tested and optimised. Whereas it is basically possible to create in each software (ArcGIS and HMC+) new archaeological entities with different identifiers, a unique identifier for each of these entities is necessary. Therefore, a hierarchical model of data input had to be defined and optimised for standardised digitisation, segmentation and the interpretation workflow. To prevent double-naming and contradictions, data input not according to the hierarchical model and standard procedure will be restricted by the AIS. Depending on the specific demands and possibilities of the digitisation workflow, principal properties of the basic (analogue) datasets, observed reliability of the datasets and archiving concept, a geodatabase (GDB) prototype has been developed. All digitally recorded SUs will be stored within this ArcGIS GDB and related to all available archaeological information. The GDB will store raster classes (based on drawings, topographical models, aerial imaginary, photographs, etc.) and feature classes (point, line and polygon) together with respective attributable information to guarantee data queries and display and correlate specific spatial information with the temporal information stored in HMC+. Once the data is digitised, segmented and embedded, the AIS should be capable of guaranteeing more efficient study of documented archaeological information. On this basis an interpretation of the spatio-temporal correlations of SUs, including concepts of functionality covering large areas, could be done and visualised.

Digitisation and Segmentation

Three tasks for the implementation of the legacy dataset of Tell el-Daba into the proposed AIS can be distinguished. (1) The analogue data has to be digitised. This procedure has to be optimised to the most practical resolution for each dataset. (2) The digital data has to be geo-referenced for import into the GIS-based AIS. (3) The data has to be segmented digitally according to specified and well-defined rules.

A GIS project was set up according to the geographical coordinate system used in Tell el-Daba since 2008.[33] All geographic transformations were based on this coordinate system. For a general overview of the area and to ensure control of the uploaded and geo-referenced data, aerial and satellite imagery were included. All drawings (level drawings, cross-sections and detailed drawings) were scanned, partly assembled in Adobe Photoshop and geo-referenced in ArcGIS 10.2. Rectification of the drawings was tested but proved not to be relevant in terms of accuracy.

Most maps were drawn in the scale 1:50, which corresponds to a resolution dependent on the thickness of a line drawn by a pencil or crayon. Based on this a precision of more than 5cm has to be taken into account, whereas accuracy depends on the respective archaeological setting, the skills of the drawer and used recording equipment. It should be expected within a range of approx. 5–10cm. For the data of square j/21 we decided to digitise all features, including single bricks, artefacts and bones with polygons. The digitisation of every brick was opposed by some

[31] For further information and to download trial version refer to Harris Matrix Composer.
[32] Traxler – Neubauer 2008.
[33] Kurtze 2008.

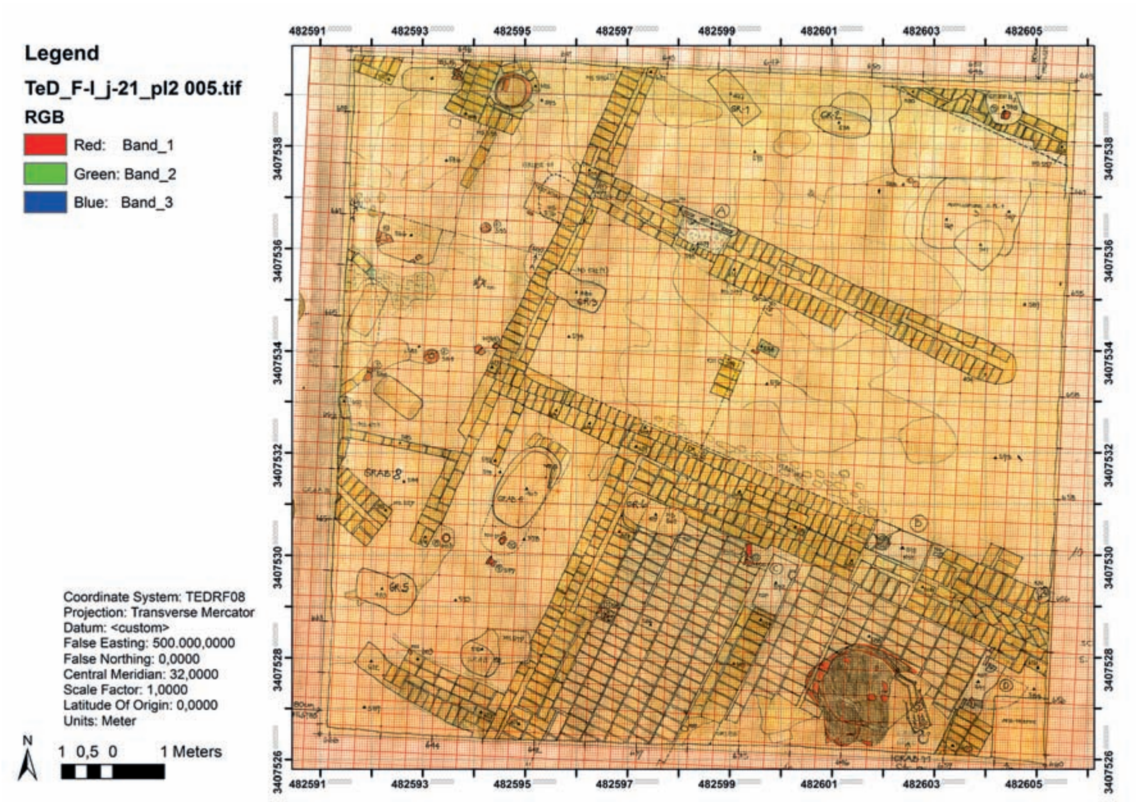

Fig. 4 After digitisation level drawings in the scale 1:50 are imported and georeferenced for further treatment in GIS. The drawing of level 2, square j/21 (LBI ArchPro)

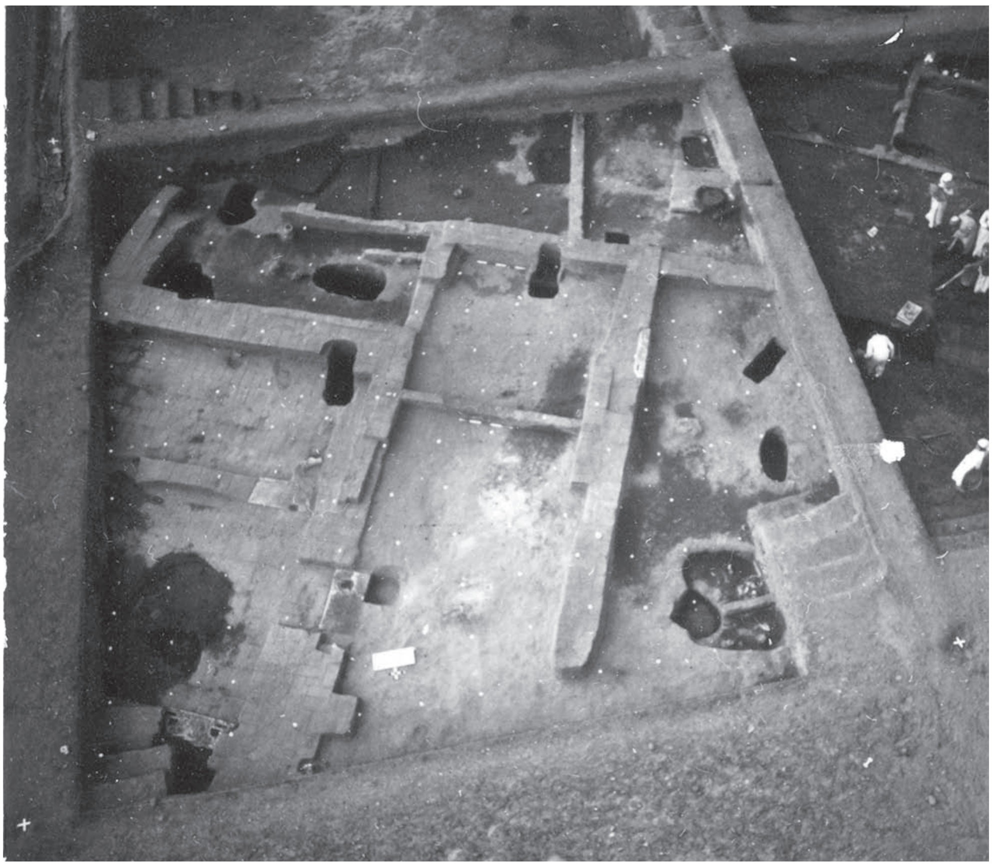

Fig. 5 Overview image of level 2, square j/21 (OREA archive)

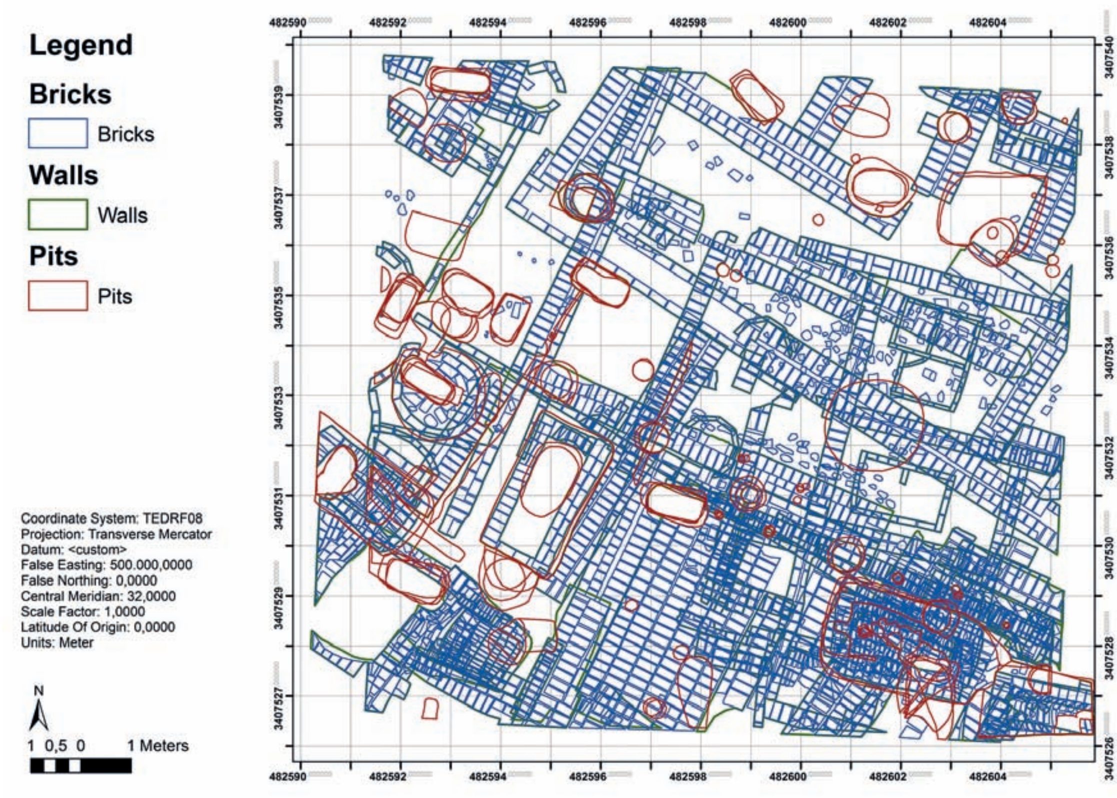

Fig. 6 Digitised bricks, walls and pits of all levels of square j/21 (LBI ArchPro)

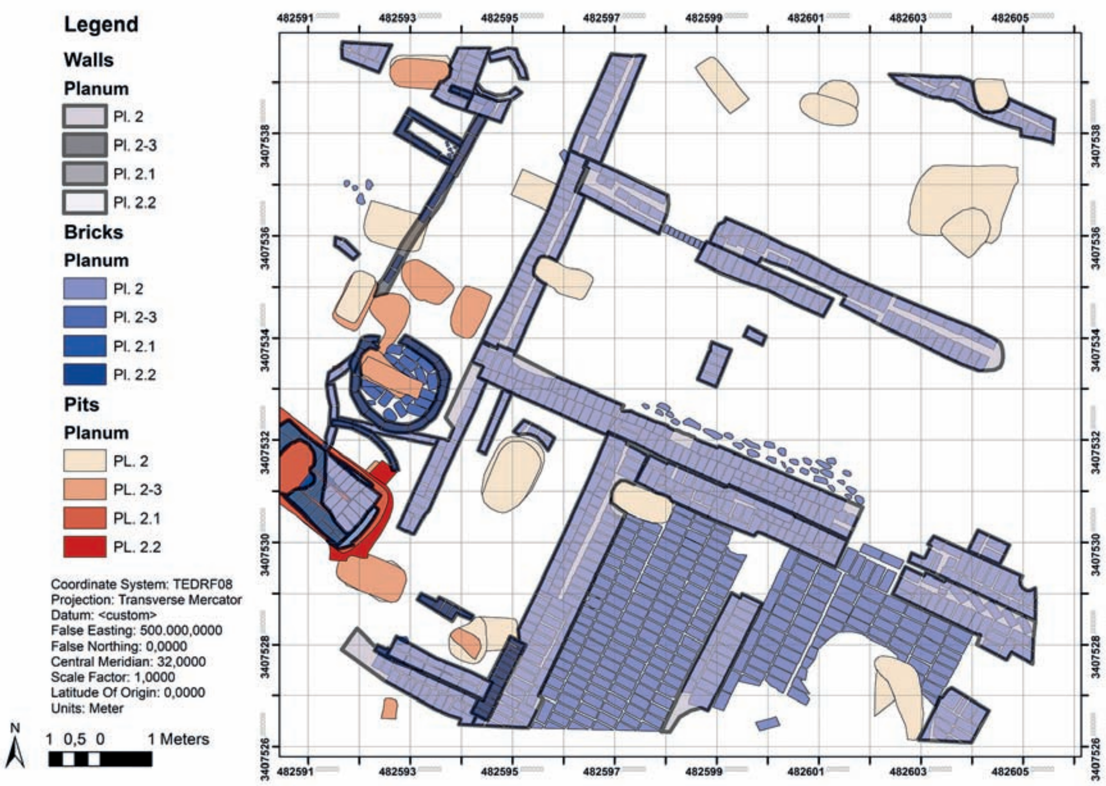

Fig. 7 A schematic map of pits, walls and bricks documented on level 2, square j/21 (LBI ArchPro)

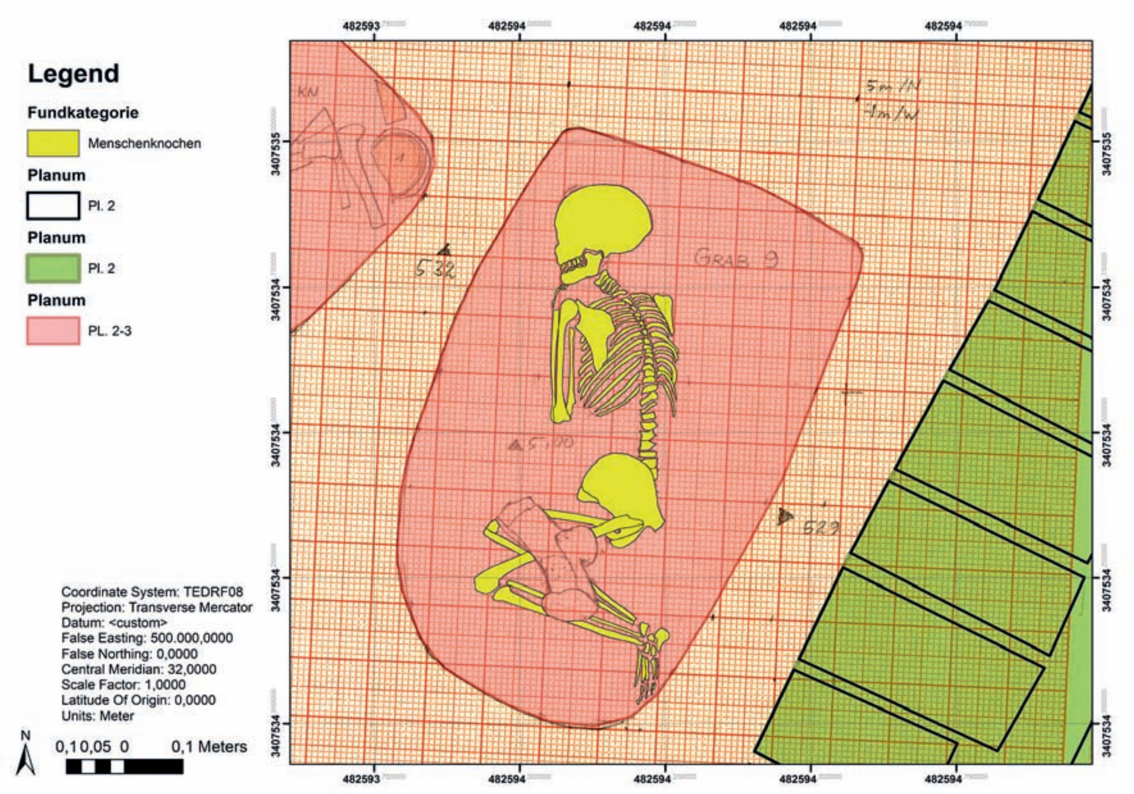

Fig. 8 Digitisation of a field drawing. Grave 9 in square j/21 (LBI ArchPro)

Fig. 9 Photograph of grave 9, square j/21 (OREA archive)

as an enormous expenditure of time and hardly achievable for the whole area regarding cost and time efficiency. Additionally, a single brick within a wall bond is rarely seen as a single SU in archaeological interpretation. Nevertheless, the analysis of the type, material and location of a brick specifies the functionality and spatial relations of a wall, information that is recorded in drawings. The question of whether to digitise only walls or also bricks is dependent on the expected degree of confirmability and reproducibility of gained archaeological interpretations through a quantitative approach. To investigate the benefits and advantages many approaches were evaluated.

The segmentation and vectorisation of the data was done in ArcMAP 10.2, resulting in polygons for every observed feature.

The extension of the features in z-direction was derived from measured heights in the drawings and educated guesses, e.g. the thickness and size of bricks are more or less comparable. At first all types of analogue but also digital data of one square (j/21) in area F/I were integrated in the AIS and all features digitised. In the second step, information regarding a specific phase (stratum d/1.1) of the whole area of F/I was digitised, representing the presumed structures of the palace, surrounding infrastructure and graves mentioned earlier.

For the development of a GDB all information on hand was collected and included within the attribute tables of every feature class. On the basis of the collected information data was classified according to thematic separation of different feature classes, including SUs (walls, pits and layers), bricks, building parts and finds. Additionally, a separate feature class was created to mark the position of the sections. Each attribute table of the different feature classes displays archaeological information about a feature derived from the drawings (e.g. the used colour code indicates specific material), the field protocol, cross-sections and photographs. Further attributes hold available metadata, e.g. source, filename or identifiers of documents and archaeological and excavation objects. One important source of information was personal communication with the Tell el-Daba researchers at the Institute for Oriental and European Archaeology (OREA).

The main aim of providing detailed information in these attribute tables is to guarantee reproducibility of archaeological analysis and interpretation of results as well as prepare the data for the following archiving process (e.g. adding identifiers that comply with the metadata format developed by OREA). The attribute tables provide the basis for the design of the Tell el-Daba-specific GDB which will be used to digitise further areas of Tell el-Daba excavations for stratigraphic analysis. So far the digitised dataset of square j/21 consists of nearly 4,500 recorded features separated into the aforementioned six different feature classes.

For testing and developing the described workflow procedures as a basis for spatial and temporal expert analysis in a 4D AIS within a larger area, another subset of the data was chosen. All data available from a specific archaeological phase was digitised, namely Tell el-Daba phase G/4 (stratum d/1.1), represented by a palace and tombs in area F/I. This subset consists of the data of 40 squares (i/20-23, j/20-23, k/19-23, l/16-21, m/17-20, n/17-21, o/16-21 and p16-21), including square j/21.

All relevant field drawings were collected, scanned, imported and geo-referenced in ArcGIS according to the Tell el-Daba coordinate system. In most cases, only one arbitrary level, planum, representing stratum d/1.1 was considered. Additionally, the general AutoCAD map and a generalised overview map (ink drawing) of the stratum were imported and geo-referenced. Based on previous experiences regarding the digitisation of all bricks in square j/21, only the outlines of the walls were vectorised. Since digitisation of every single brick requires much time, whether comparable results could be derived on the basis of a reduced digitised dataset was also questioned.

As for j/21 a GIS database containing more or less the same columns for data and metadata was established. If available, additional information deducible from cross-sections, the handwritten record and publications was embedded in the database. So far more than 500 features numbered consecutively with respect to the already digitised dataset have been listed in the database.

The digitisation process, including the recording of heights indicated in drawings and cross-sections, results in volumetric features. Archaeological information concerning every feature is available in the database. Based on these properties the spatial superposition of observed features can be derived and SUs defined. A stratigraphic sequence of all recorded features is yet to be done. For this purpose flexible visualisation and display of single volumetric features are crucial.

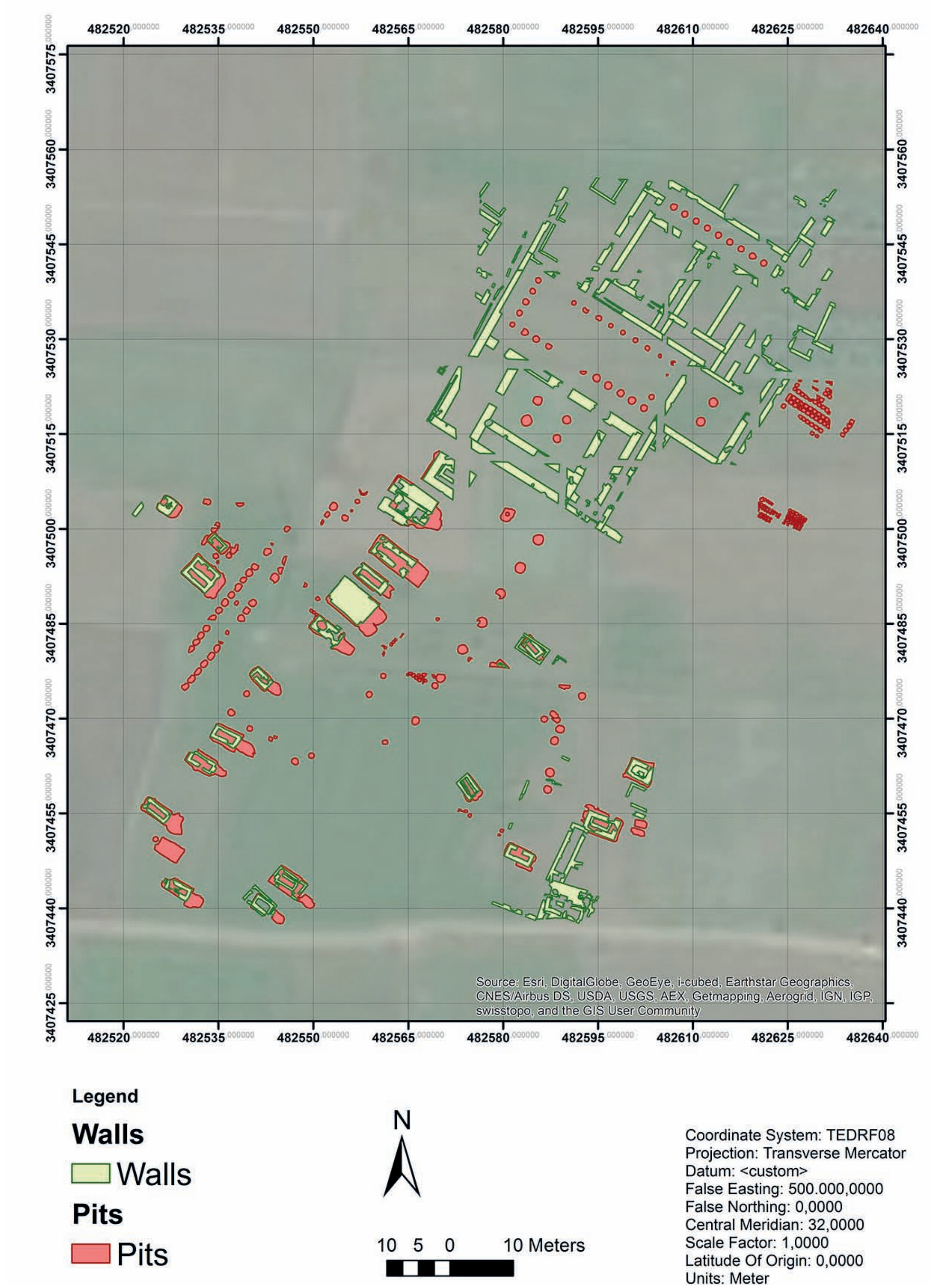

Fig. 10 Phase map of stratum d/1.1 displaying pits and walls of the respective squares (LBI ArchPro)

Visualisation – Spatial and Temporal Relation

Within each feature class of the database of both subsets the attributes’ extrusion and base height for volumetric representation are included. These are relevant for the display of digitised features and structures as volumes in ArcScene 10.2. This depiction mode allows the visualisation of entities from different arbitrary documentation levels in 3D at the same time. Displaying and visualising spatial superposition of recorded 3D volumes is a powerful tool for archaeological interpretation from which SUs can be specified. The stratigraphic sequence is generated within by HMC+ software.

As a matter of fact, a feature might be recorded within several drawings that all represent the same SU. In this case it had to be merged into one SU. According to the observed spatial superposition of the digitised features a stratigraphic sequence was generated. The cross-sections were used to gain additional information about 'missing' SU. As the excavation was carried out in discrete levels of approx. 20–40cm apart, most of the stratigraphic information between these levels had been removed. In this sense the Tell el-Daba dataset was incomplete regarding the loss of surfaces

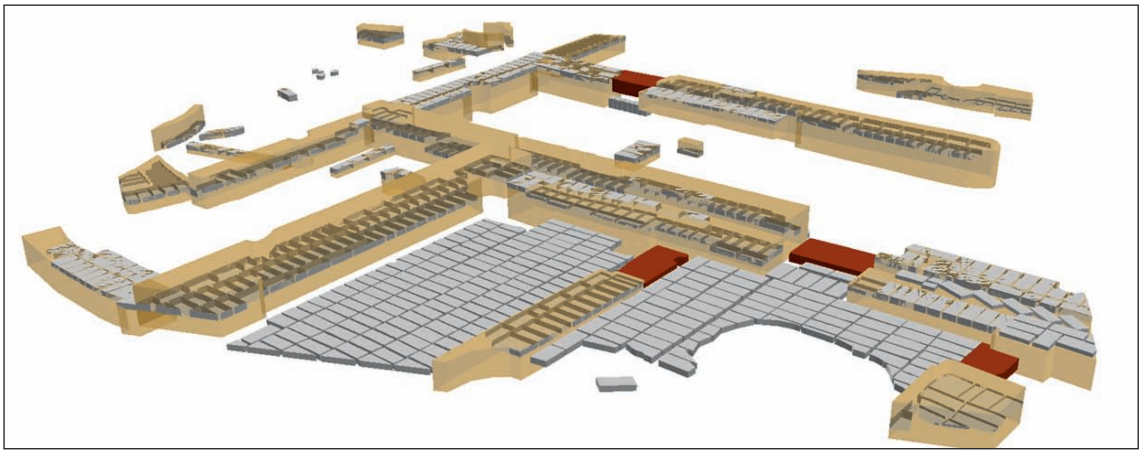

Fig. 11 In adding height information indicated in the drawings, structures could be extruded to generate volumetric stratigraphic units. This simple geometry is sufficiently displayed in ArcScene (LBI ArchPro)

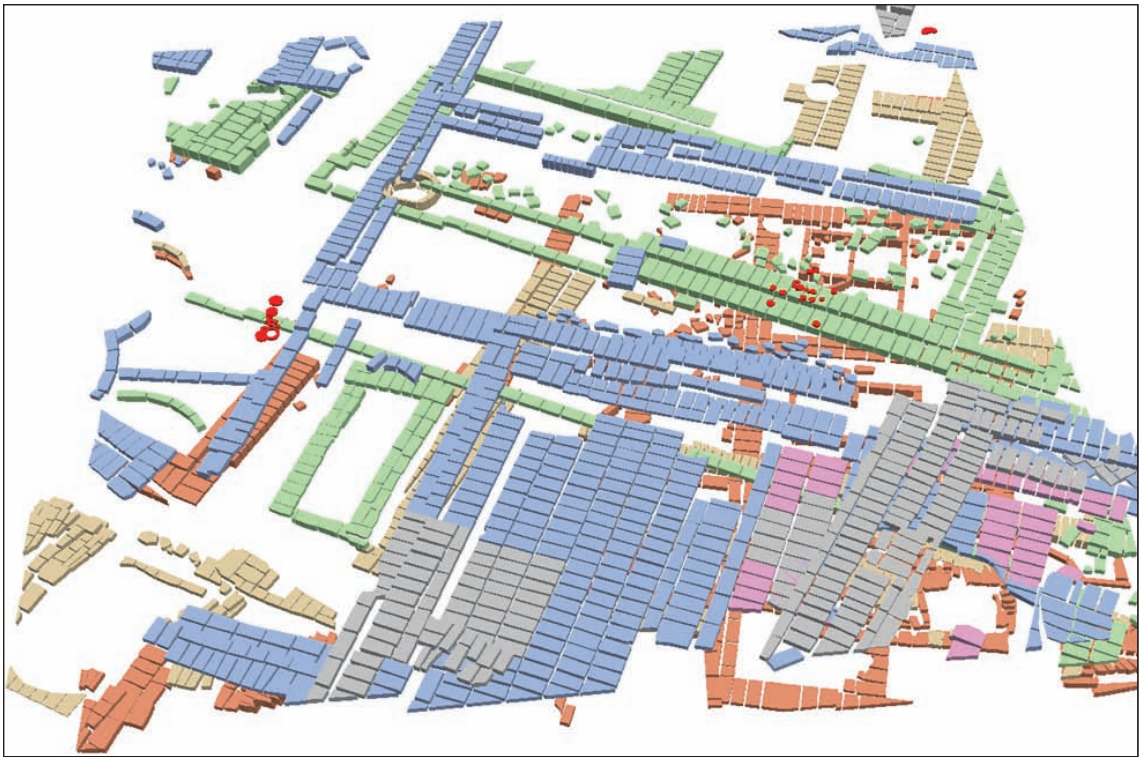

Fig. 11a Spatial superposition of bricks belonging to different archaeological phases (LBI ArchPro)

and enclosed volumes due to the selective excavation process. The infill of a room was removed for example down to its presumed floor. When a room was artificially separated by a trench or occasionally cut purposefully by an additional cross-section, the archaeological evidence of the stratigraphic sequence lost within these volumes became visible. Parts of lost sequential information could be reconstructed through the analysis of the cross-sections (e.g. primary and secondary use and decay of a structure could be observed and represented within a stratigraphic sequence).

For further investigation of spatial relations and to display additional information, e.g. from sections, complex tomb constructions were visualised with the free software SketchUP (Trimble). These detailed reconstructions were made for three tombs and a cellar recorded in square j/21. Using SketchUP all drawings (details, side views and sections) can be displayed at the same time according to their geographical position. Based on these drawings 3D models of the specific structures were derived. The surfaces could be textured according to colour codes or a more realistic texture. Finally, each 3D model can be imported into ArcScene for further analysis of the stratigraphic sequence.

Once the spatial superposition is represented correctly within the stratigraphic sequence, the temporal attributes of each SU can be set according to the specifications of HMC+, which base strictly on the principles of stratigraphy. Each SU can be either assigned to an archaeological phase or defined by specific start and end dates. It is therefore possible to run a query regarding temporal and spatial attributes. To observe the functionality, use and decay of the features for expert archaeological interpretation, the display of different assumed phases is extremely helpful. The temporal relations allow displaying features, which are not in direct spatial superposition. This is crucial for the analysis of the relation of different structures spread over a large area (e.g. houses in a settlement).

For a better depiction of archaeological interpretations and reconstructions simple but meaningful software called Arch4DInspector was developed. It basically allows the user to switch between all archaeological data used in the modelling process while observing a reconstructed 3D model on top. The interface consists of buttons that allow the user to enable and disable different types of information transparently layered on top of each other, a slider for depicting the 3D model through time and a button that orbits the camera around the data and 3D objects for better inspection. Suggested reconstructions and spatial and temporal relations of different phases could be displayed online.[34]

Results

So far more than 5000 archaeological features have been digitised in ArcGIS 10.2. During this process several factors were monitored. One of the main issues of the project is to develop a standardised digitisation workflow, which is crucial for complete and redundant digitisation and later interpretation of the Tell el-Daba legacy dataset. All necessary individual operations were defined based on the demanded skills of the person in charge, which was necessary for effective planning of the project to digitise and spatially segment the whole Tell el-Daba dataset.

An initial database was designed to determine the design of the GDB, which is among the recent tasks of the project and still under development. Data formats, syntax and filenames of feature and raster data have been defined according to the archiving routines carried out by OREA.

Several structures were digitised in 3D using SketchUp. The resulting 3D objects illustrate the situation as they were found when excavated or an idealised view representing a moment during their use. Whereas the former could be time-consuming, a simple 3D model is mostly sufficient for further proper analysis to generate a stratigraphic sequence. These models could be easily

[34] Torrejón-Valdelomar et al. 2015.

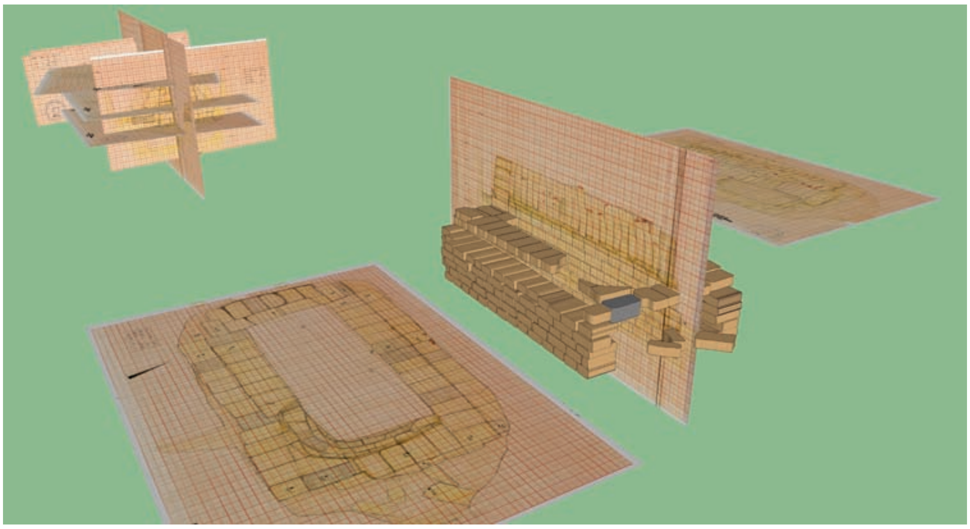

Fig. 12 Drawings of cross sections are displayed in SketchUP to reconstruct archaeological structures. Grave 13 of square j/21 (LBI ArchPro)

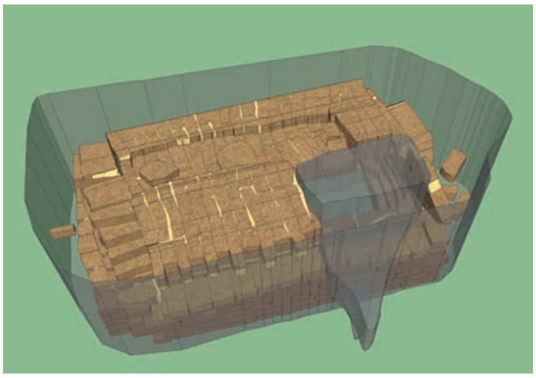

Fig. 13 Remodelling of grave 13 in SketchUP (LBI ArchPro)

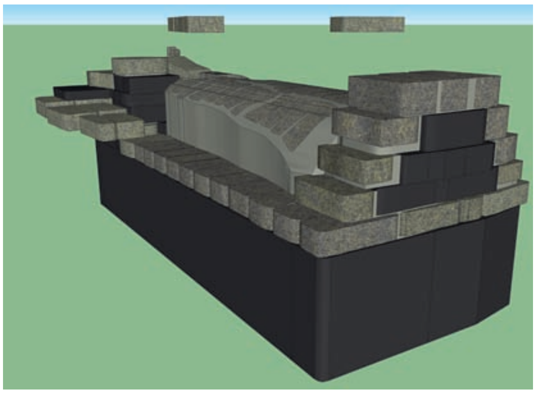

Fig. 14 Idealised reconstruction of grave 13 (LBI ArchPro)

Fig. 15 Grave 13 as it was found during excavation (OREA archive)

derived within the AIS by extruding the digitised features according to their observed height, as height measurements from drawings are stored in the GDB. This is necessary to reconstruct the spatial component of the stratigraphic sequence also within areas where this information had been lost due to the excavation process. Arch4DInspector proved to be a very handy tool to dis-

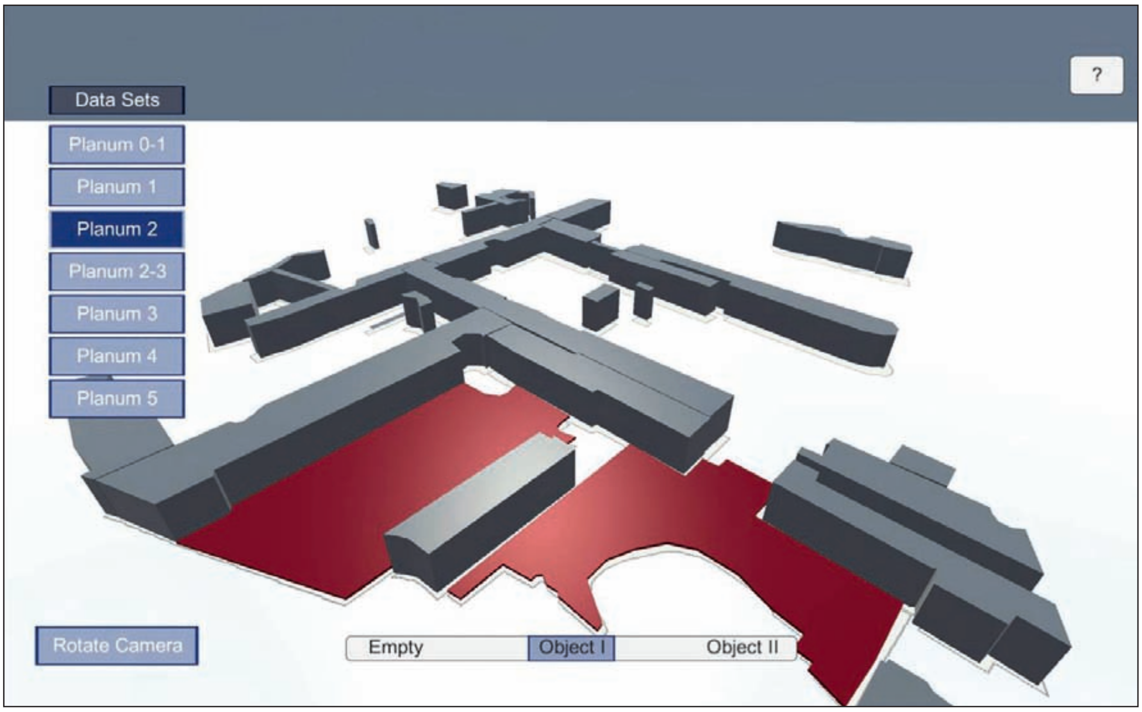

Fig. 16 Screenshot of Arch4D. This tool allows displaying 3D models together with additional information (e.g. drawings as base layer). It is also a web-based viewer (LBI ArchPro)

play basic source information from drawings of levels and cross-sections together with simple reconstructed volumes to visually control spatial consistency. The hypothetical character of the reconstructed volumes must be emphasised.

After the digitisation of the selected subsets, namely square j/21 and area F/I, the spatial and temporal superposition was examined and reconstructed, leading to a mathematically valid stratigraphic sequence.[35] For this purpose the software HMC+ was updated and complemented with a temporal model based on time intervals. Based on observations regarding the reconstruction of the incomplete legacy dataset qualitative guessing of the reliability of the various data sources could be derived. The sections proved to be an important qualitative pool for further information about undefined SUs.

The average precision and especially accuracy of the data are not quantifiable. Precision regarding the spatial resolution is related to the scale of the drawings and the recorded situation, resulting in an estimated error range of 5–10 cm. Contradictions within the legacy dataset, e.g. physically impossible spatial superposition of SUs documented in the cross-sections and the level drawings respectively, could be detected through analysis of the reconstructed stratigraphic sequence.

For the reconstruction of a valid stratigraphic sequence the suggested structure of an AIS, including ArcGIS, HMC+ and a GDB, specified to the demands of the Tell el-Daba project proved to be very efficient. In setting up a GIS-based AIS every item of the digital archive will be specified by its geographical location, as the basis for further archaeological interpretation of the dataset as well as for a comprehensive virtual reconstruction of the site.

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35 The validation of a stratigraphic sequence is mathematically argued. As the primary stratigraphic information is lost through archaeological excavation, the stratigraphy represents the observed stratification of the archaeological site and is therefore always interpretative and hypothetical. The hypothetical stratigraphic sequences derived from the spatial and temporal analysis supported by the GIS-based AIS are valid in respect to the laws of stratification.

Conclusions

Legacy excavation data are in most cases incomplete compared to recently derived datasets. Regarding the complete description and segmentation of an archaeological stratification, volumes must be reconstructed where data are missing. A stratigraphic sequence has to represent the whole excavated archaeological volume, i.e. complete stratification. An AIS strongly represents possibilities for remodelling unrecorded information. This process can be described as reverse excavation in comparison to the term reverse engineering, where from a real model an idealised one is deduced.

In transforming the legacy dataset according to present-day methodology in a standardised and well-documented way the new data and results become comparable with other datasets. Comparability is indeed one of the central demands when analysing data and proposing new archaeological interpretations and theories. These results must be also reproducible and comprehensive. These traits become possible by the organisation's introduced system and correlation of archaeological information within a GDB. During the digitisation of the data and spatio-temporal analysis, resulting in a stratigraphic sequence, the reliability of specific properties from the different sources was observed. For example, some section drawings were idealised in order to highlight observed correlations. This has to be taken into account when trying to describe and define the accuracy of digitised data.

The components and specifications of the GIS-based AIS facilitate the analysis and documentation of the spatial and temporal properties of every SU. Each documented SU is uniquely identified by its geographical location, which also refers to its spatial superposition. Temporal properties of archaeological features, structures and processes are interval-based. Allen's interval algebra mathematically defines the relations of intervals and is therefore perfectly suited for the analysis of respective temporal relations. In this way the description and analysis of spatial and temporal properties allow interpreting archaeological information in 4D.

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