



Re-enacting the sequence: combined digital methods to study a prehistoric cave

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Abstract

This contribution seeks to demonstrate how recently developed 3D GIS platforms can help archeologists in relating to the original context legacy data that can be employed to digitally reconstruct the sequence of arbitrary layers as it was observed and then excavated in the end of the nineteenth century. This research has been conducted on the prehistoric cave of Stora Förvar, located on the small island of Stora Karlsö, in South-Eastern Sweden. As a part of a research project titled “The pioneer settlements of Gotland,” this line of enquiry has sought to combine 3D-based digital acquisition techniques, Geographical Information Systems (GIS), and old archival material (hand-made drawings, artifacts lists, historical pictures) in order to virtually reconstruct the original sequence as it was excavated through the method of arbitrary layers. At a later stage, the reconstructed sequence has been employed to re-contextualize and analyze the distribution of artifacts so as to detect any possible pattern that could have been useful for defining the chronological boundaries of the Mesolithic phase of habitation of the cave. In brief, three main objectives can be defined: (a) to re-create a spatial connection between the artifacts retrieved at the time of the excavation and the sequence of layers, (b) to define density maps showing the relationship between volumes of layers and categories of artifacts belonging to the sequence, and (c) to further our knowledge about the Mesolithic habitation of the cave, not only vertically (chronologically) but also horizontally.

Keywords 3D GIS · Mesolithic · Scandinavian archeology · 3D spatial analysis · Volumetric analysis

Introduction

This contribution seeks to demonstrate how recently developed 3D GIS platforms can help archeologists in relating to the original context legacy data that can be used to virtually reconstruct and interpret the sequence of arbitrary layers as it was observed and then excavated in the end of the nineteenth century. This research has been conducted on the Prehistoric cave of Stora Förvar, located on the small island of Stora Karlsö, in South-Eastern Sweden (Fig. 1). As a part of a research project

titled “The pioneer settlements of Gotland,” this line of enquiry has sought to combine 3D-based digital acquisition techniques, Geographical Information Systems (GIS), and old archival material (hand-made drawings, artifacts lists, historical pictures) in order to virtually reconstruct the original sequence as it was excavated through the method of 30-cm-thick arbitrary layers. At a later stage, the reconstructed sequence has been employed to re-contextualize and analyze the distribution of artifacts so as to detect any possible pattern that could have been useful for defining the chronological boundaries of the Mesolithic habitation of the cave.

The pioneer settlement phase of Gotland extended between 9200 and 7600 BP. The cave site of Stora Förvar was according to a summed probability distribution analysis based on 65 C14-dates dated to the period 9200–7800 so the cave was abandoned earlier than the settlements on Gotland Island, probably because of the effects of the Litorina I transgression (Apel et al. 2017). The cave site of Stora Förvar is unique and has played a key role in understanding the Stone Age of Gotland. The cave sequence of Stora Förvar was excavated

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Fig. 1 The cave site of Stora Förvar is located on the island of Stora Karlsö, in the Baltic Sea, South-eastern Sweden (© Lantmäteriet, Swedish cadastral agency; freevectormaps.com)

between 1888 and 1893 by Lars Kolmodin and Hjalmar Stolpe. Unfortunately, the final excavation report was not published until 50 years later by Bror Schnittger and Hanna Rydh (1940), who had not participated in the actual fieldwork. However, Hanna Rydh had carried

out her own excavations on Stora Karlsö and was well aware of the archeology of the island. Already in 1926, Adolf Pira published the first analysis of faunal remains from the Stora Förvar cave. He investigated the seal bones in the cultural layers and noticed that the

frequencies of seal bones from different species varied over time. For the present study, we will focus attention on the presence of harp seal, a species that entered the Baltic basin some 6000 years BP. This coincides roughly with the time when the cave was resettled again in the Late Mesolithic/Early Neolithic. Thus, the bones of harp seals are an important chronological proxy to distinguish the Neolithic layers of the cave, together with pottery and also harpoons.

One of the main aims of the “The pioneer settlements of Gotland” project has been to evaluate the integrity and character of the Mesolithic component of the cave sequence Stora Förvar. As part of the project, a small excavation was carried out in summer 2013 and a digital 3D scanning of the cave was made (Apel et al. 2015; Apel and Storå 2017a, b). We had on previous visits found bones and stone in the soil layers of the cave floor, which suggested that there could be preserved cultural layers pockets that had not been excavated. The purpose of the field work was to investigate this further by performing limited test excavations. Three smaller trenches were excavated of which two contained pristine Mesolithic layers. The content of the test trenches was sieved through 4- and 2-mm meshes and the find material was documented in units of 0.5×0.5 m and 5-cm spits. The layer that was encountered was interpreted as being homogenous, but with intrusions of chalk that had penetrated the soil with water that is dripping from the cave walls (Apel and Storå 2017b). The quality of the bone material and two flint blades that could be refitted are indication of the stratigraphic integrity of the layer (Apel and Storå 2017a). A mobile 3D-scanner was used to build a digital, three-dimensional model of the cave (Lundström 2016; Landeschi et al. 2018). We here evaluate the potential of combining information from the 3D-technique with data in the archival material from the excavations in order to highlight the Mesolithic use of the cave. The purpose is therefore to take advantage of an entirely three-dimensional environment: (a) to re-create a spatial connection between the artifacts retrieved at the time of the excavation and the sequence of layers, (b) to define density maps showing the relationship between volumes of layers and categories of artifacts belonging to the sequence, and (c) to further our knowledge about the Mesolithic habitation of the cave.

Methodological framework

Theoretical background

In the last few years, an increasing interest on the combined use of techniques for collecting and analyzing archeological data has been characterized by the significant advances occurred in the

field of Computer Science (Dellepiane et al. 2012; De Reu et al. 2013; Dell’Unto 2014). Site acquisition and documentation strategies have been enormously improved thanks to the adoption of innovative methodological approaches (Dellepiane et al. 2012; De Reu et al. 2013; Dell’Unto 2014; Katsianis et al. 2008; Callieri et al. 2011; Opitz and Nowlin 2012; Campana 2014; De Reu et al. 2014), which contributed to reinforce reflexivity in the practice of archeological excavation (Hodder 2000); this also raised up additional questions on which contribution three-dimensionality could provide to archeological research (Forte et al. 2012; Berggren et al. 2015). In particular, based on the recent advances in digital technology, there is an increasing “heuristic” potential connected to the use of three-dimensionality in archeology which could lead to interesting openings in the field of spatial data analysis, as predicted by some authors a few years ago (Gillings and Goodrick 1996; Frischer 2008). Recently, the introduction of more advanced 3D GIS software, namely ESRI ArcGIS 10.x package (ESRI 2015), opened new ways of analyzing archeological data, by combining spatial analysis tools and geometrically complex 3D boundary models (Landeschi 2018; Landeschi et al. 2016b; Dell’Unto et al. 2015). Such an achievement led to a more accurate representation of the material evidence and novel methods of analysis were experimented in order to investigate spatial relations in field excavation (Wilhelmson and Dell’Unto 2015), to perform visibility analysis in a reconstructed architectural space (Landeschi et al. 2016a) and to assess structural degradation in historical buildings (Campanaro et al. 2015). Another relevant aspect is the multiscalarity of the dataset, where analysis can be performed either on the single artifact or extended to the whole landscape in the same georeferenced space. Indeed, by adjusting the size of the polygonal mesh associated to each 3D model, it is possible to optimize the model representation in relation to the scale of analysis. Remarkably, the prehistoric caves constitute an interesting case study to observe the advantage of such an approach, due to the complex environmental settings in which traditional methods of survey fail in providing an adequate representation on the original space.

Background in cave studies

As reported by several authors, archeologists have tried to introduce digital technologies in the study of Prehistoric caves (Galeazzi and Moyes 2011; Galeazzi et al. 2014). Still, a very limited number of studies succeeded in combining 3D and GIS-based methods. An interesting example of the combination of different acquisition techniques is given by a research conducted in a Paleolithic cave in Spain, where Terrestrial Laser Scanning (TLS) and close-range photogrammetry have been combined together to provide archeologists with an accurate dataset of information that represented a significant step forward compared to traditional, bi-dimensional methods of documentation (Lerma et al. 2010). Similarly, a multi-

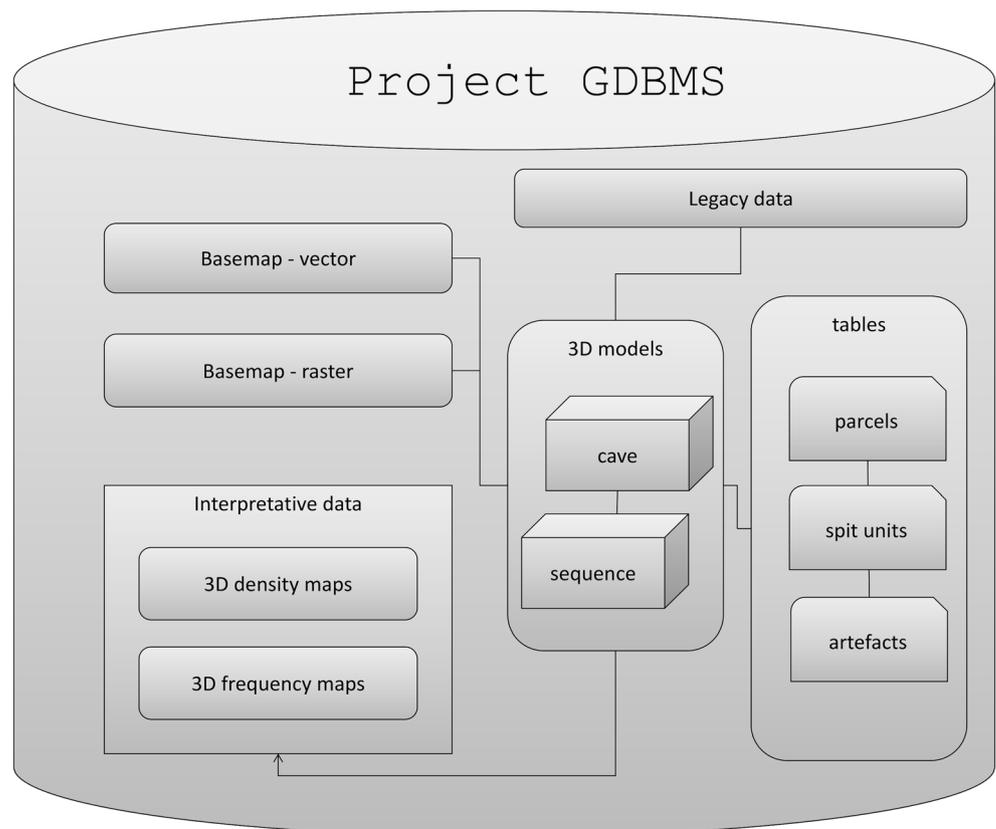


Fig. 2 The terrestrial laser scanner employed for the acquisition (Faro Focus 120S phase shift variation 3D-scanner) placed at the entrance of the cave as it looks today

resolution laser scanner combined with a digital camera was employed to provide a high-resolution textured 3D model for the analysis of pictographs observed within the Neolithic cave of Grotta dei Cervi, Italy, and this represented an interesting case in which digital methods were used to document

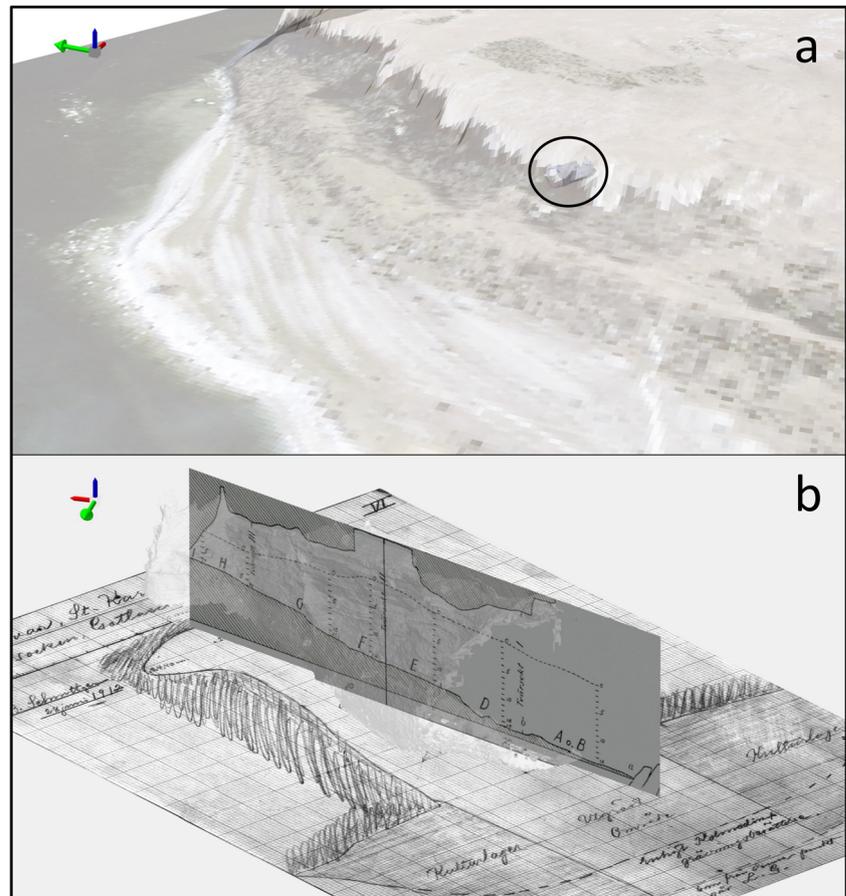
Prehistoric rock art (Beraldin et al. 2006). Analogously, the adoption of GIS-based methods and tools for investigating Prehistoric caves, allowed archeologists to quantitatively explore relations between artifacts, human remains and their original contexts, by taking advantage of the spatial information derived in the process of site documentation (Herrmann 2002; Moyes 2002). One of the main limitations in this approach is still represented by the lack of three-dimensionality, which does not allow to properly observing the physical relationships among the objects being excavated. Furthermore, this prevents from fully understanding problems related to the artifacts distribution along the z-axis, such as their vertical movement through the deposits (Hiscock 1985). More recently, some attempts of virtually reconstructing a stratigraphic sequence in combination with a cave 3D model have been done in the frame of a research project developed in the Pastora cave, Eastern Spain (Puchol et al. 2013). By combining old site documentation sources, it has been possible to reconstruct and spatially locate the cultural layers dated between the Neolithic and the Bronze Age. Still, due to the lack of a method of excavation based on stratigraphic units (it was conducted during the 1940s by an amateur archeologist), it was not possible to define the original appearance of the deposits and the layers were basically defined by the plans on which the artifacts were laying at the time of the excavation. Nonetheless, some important advances have been showed in the way 3D

Fig. 3 ESRI ArcGIS geodatabase management system (GDBMS) has been set up to integrate different datasets: basemap layers made by vector and raster cartographic data, legacy data in the form of scanned hand-made drawings, tables containing information on artifacts distribution throughout the sequence, and 3D multipatch feature classes of the cave and the reconstructed sequence. Output data have been finally derived and used in support of archeological interpretation of the site



visualization has been adopted to locate and display artifacts in relation to their original context and in their reciprocal position in the space of the cave. This would be a good example on how 3D-based methods might be used in support of museum communication, where visitors could better understand issues related to the different phases of inhabitation of a Prehistoric cave. To sum up, there is an increasing acknowledgment of the role that 3D and GIS-based methods have in the process of site documentation and data analysis. Still, more studies need to be carried on in order to effectively explore the potential derived from the combination of both of them. Despite a general acknowledgement of the importance of using digital methods as a way to improve the documentation strategies, there is still a lot of work to be done, in order to effectively use three-dimensionality as an additional factor in support not just to data visualization but also, for the analysis of archeological evidence and its original context. As this contribution seeks to demonstrate, the integration of 3D technology and GIS platforms could provide significant advantages in the study of prehistoric caves and their related material, enhancing the possibility for archeologists to investigate relations and interactions among the objects, along the full space of x , y , and z Cartesian coordinates, in a way that would not be possible with bi-dimensional site documentation methods.

Fig. 4 Different datasets have been integrated to generate the final three-dimensional sequence as it was excavated in the end of the nineteenth century. In ESRI ArcScene, a LIDAR-derived DEM has been used to contextualize the 3D model of the cave in the surrounding landscape of Stora Förvar (a) (© Lantmäteriet, Swedish cadastral agency). Then a combination of digitally scanned and georeferenced original plan and profile drawings gave the possibility to exactly reconstruct the 30-cm-thick layers and to rename them based on the original excavation reports information (b) (© Antiquarian Topographical Archives in Stockholm)



Acquiring the cave

In the summer of 2013, the cave Stora Förvar was acquired by means of terrestrial laser scanner. A Faro Focus 120S phase shift variation 3D-scanner was employed (Fig. 2). Each scanning position produced a point cloud with 12 million points. Due to the short timeframe in which the recording had to be done and the complex geometry of the ceiling of the cave, the method used was to record a relatively large number of scans to get a good overlap between them. Thirty different positions for the scanner were defined to cover the entire space of the cave. In the post processing phase, the scans were manually registered using the open source software Meshlab (Cignoni et al. 2008). The same software was also used to combine, clean, simplify, and mesh the scans in order to produce the complete 3D-model of the cave. During the recording, some easily recognized features were marked out to be measured with a total station later on, making it possible to correctly georeference the model of the cave in a 3D GIS platform.

Reconstructing the sequence

Different sources have been integrated to virtually reconstruct the sequence of layers as it was reported by Schnittger and

Rydh (1940). They basically consist of documents available at the Antiquarian Topographical Archives in Stockholm, (lists of artifacts, hand-made drawings of the site, field reports) and data derived either from laser scanning acquisition or completely generated in GIS. More information has been derived from the Swedish National Land Survey agency (Lantmäteriet 2015) in order to put the original sequence in the wider context of the landscape of Stora Karlsö. All the data have been implemented and processed through the ESRI ArcGIS 10.3 software package, which is to date the only GIS platform enabling users to effectively import and handle geometrically complex 3D boundary models, derived both from laser scanning acquisition and image-based 3D modeling (Opitz and Nowlin 2012). Here, different editing tools can be used in support of data analysis to improve the quality of data interpretation (Dell'Unto et al. 2015; Landeschi et al. 2015). To better serve the purpose of managing the data sets, a geodatabase (GDBMS) has been built and several types of sources were integrated (Fig. 3).

The data framework, based on the geodatabase standard, widely used in several archeological projects (Tennant 2007; Katsianis et al. 2008; Nekhrizov et al. 2012; Müllerova et al. 2013; Van Ruymbek et al. 2015), has been customized according to the specific needs of this project. As a result, the final users are provided with an effective tool for querying and analyzing the dataset. To this scope, different categories of data were defined and raster, vector and tabular format were designed

to better fit the informative function associated to every single layer. As a part of the basemap, information derived from the Swedish National Land Survey agency was added in order to provide a general spatial context to the site of Stora Förvar. An additional dataset has been added to collect as multipatch feature classes, all the 3D entities describing the cave. More shapefiles were then created in the process of data analysis, including those volumetric layers used to represent the three-dimensional sequence of the cave. As an additional data source, archival material was also imported into the geodatabase. This material consisted of data derived from the twentieth century field documentation that was produced and published approximately 50 years after the completion of the excavation. This dataset, which included original plans and profile drawings, provides us with a picture of how the cave sequence looked like at the time of the excavation and it was therefore a crucial element to be used in the process of reconstruction. In particular, one of the digitally scanned profile drawings was employed as a main reference to reconstruct both the vertical parcels and the 30-cm-thick horizontal units that composed the original sequence, excavated according to the arbitrary layers method (Hughes and Lampert 1977). Then an additional hand-made drawing was employed to define the original plan of the sequence and it was integrated along with the 3D model of the cave to enable a direct link between the final digital reconstruction and the artifacts information (Fig. 4).

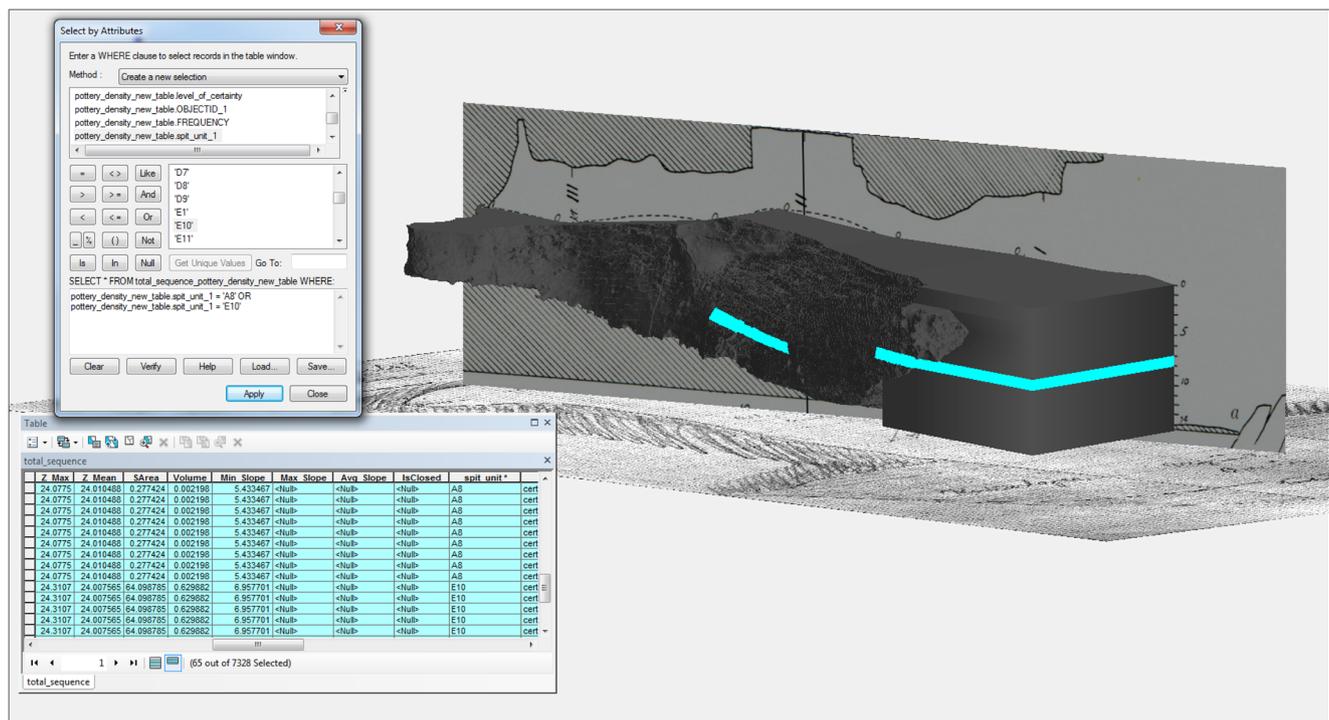


Fig. 5 As a result of the reconstruction process, the complete sequence of layers has been obtained in the form of a multipatch feature class. The relational geodatabase previously established enabled to query and retrieve information from the original arbitrary layers as they were

documented during the excavation phases. Each unit was then provided with a volumetric value and linked to the tables of finds featuring different categories of artifacts and ecofacts belonging to the sequence

Data setup

Once the data framework was designed, datasets were optimized and imported in the geodatabase. The point cloud derived from the 3D-scanned model of the cave was decimated and the original 10 million-faces mesh reduced to 1 million, in order to be better handled in the ArcScene viewer. Then it was exported as a VRML file, which is still one of the standard formats recognized by ArcGIS (ESRI 2014). In ArcCatalog, the model was converted into a multipatch feature class and added to the geodatabase. To georeference it, some total station points that had been previously collected in the field were employed. Since the main purpose of the 3D model implementation was to provide the geometric

boundaries to be used to reconstruct the sequence, no texture was added, as it would have only made the process of data visualization and management more time-consuming. Subsequently, the digitally scanned version of the original profile drawing was rescaled and turned into a multipatch feature class and georeferenced in GIS so as to spatially match the 3D model of the cave. From such a drawing information about the position, thickness and length of each single arbitrary unit was extracted and employed in combination with the 3D boundary model of the cave to reconstruct the original shape and spatial location along *x*, *y*, and *z* axes of the layers composing the sequence. Then, based on the information available, 3D shapefiles were employed to mark the original partition of the sequence in six different parcels,

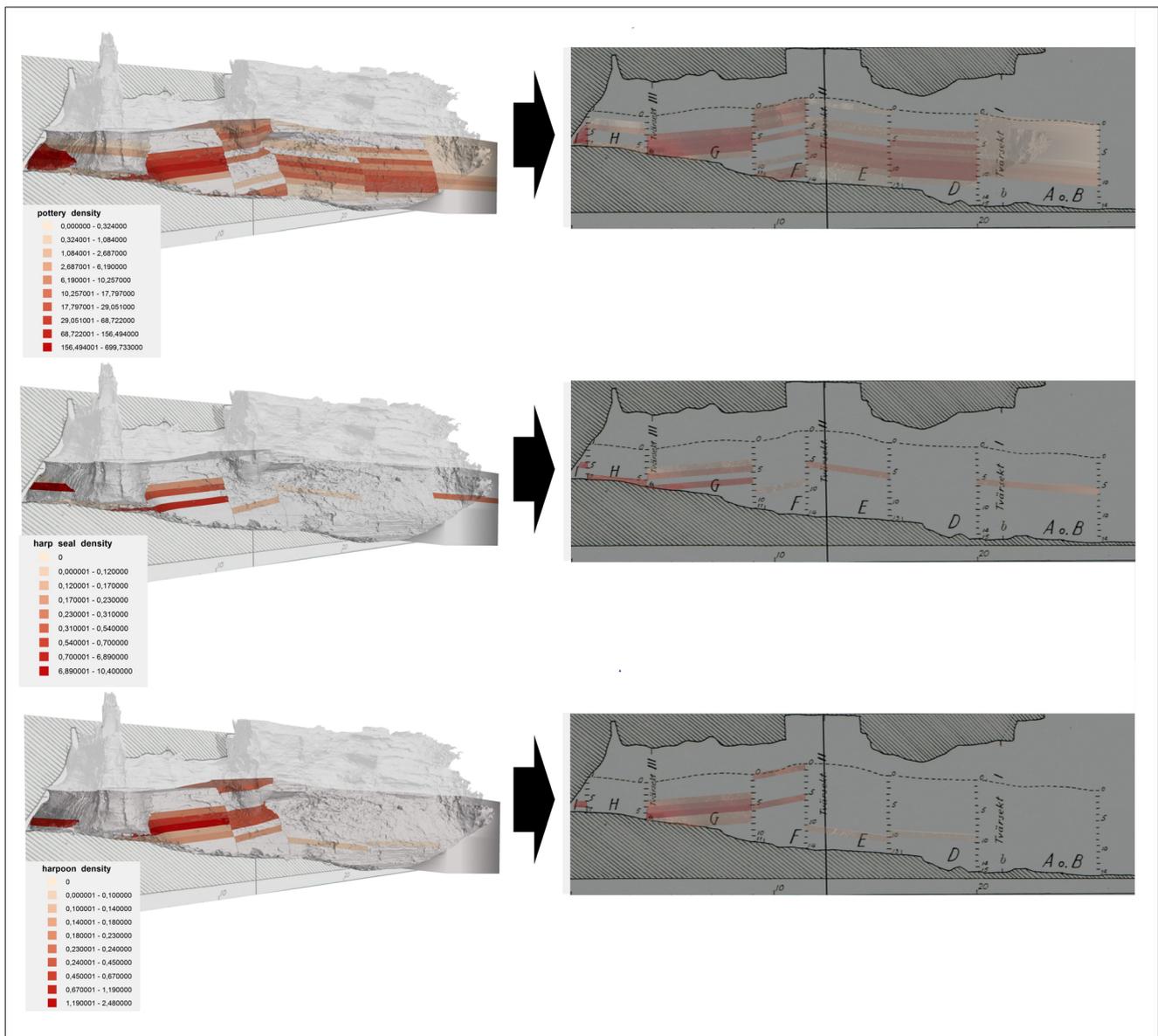


Fig. 6 Three different 3D maps of density have been produced to show the relationship between each spit unit and its content of finds. From above to below, they are illustrating the distribution of pottery, harp seal

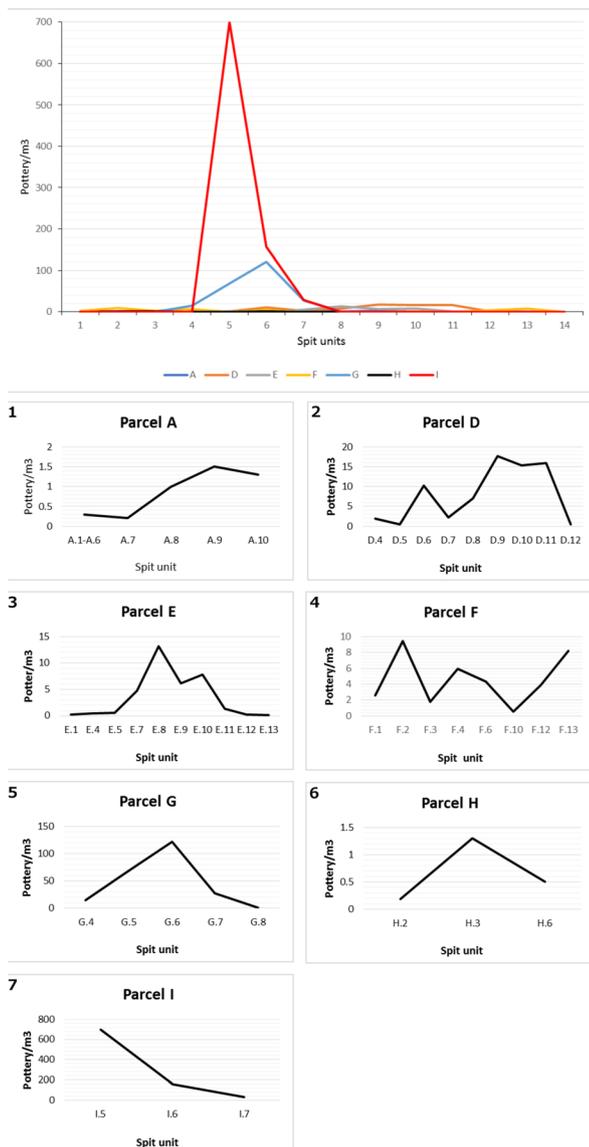
bones, and harpoons. Such information was crucial to better understand which portion of the original sequence could be connected to the Mesolithic phases of inhabitation of the cave

starting from the cave entrance to the innermost part and then marked with letters spanning from A to I. All the interface lines marking each unit boundary were converted into horizontal panels that were intersected with the mesh of the cave walls. From this intersection, polyline shapefiles were derived to represent the external boundaries of each arbitrary layer previously originated from the interface line. Each polyline was then converted into a polygon that was representing the original surface interface between two different stratigraphic units. From this polygon, a series of extrusions were employed to describe the volumetric portion of space corresponding to each unit described in the original site documentation (Fig. 5; Landeschi et al. 2018). In this way, the whole sequence of spit layers was reconstructed as it was excavated in the end of the twentieth century with each unit

containing the volume information. As a final result, all the layers were linked to the artifacts geodatabase tables, so that it was possible to define how the different classes of material were associated and distributed throughout the stratigraphic sequence. Such an operation was an essential step in the process of data analysis and this allowed us to spatially investigate the original distribution of the artifacts and to possibly detect patterns of presence linked to the different phases of inhabitation of the cave.

Results and discussion

The digital reconstruction of original spit units enabled us to calculate and assign the volumetric value to each layer. This was a



Spit unit	Total Volume excavated	Total artefact yield	Total pottery yield	Pottery density per m3	Total artefact density per m3	Pottery % of total assemblage
A.1-A.6	108 m3	70	35	0,3/ m3	0,64/ m3	50%
A.7	18 m3	14	5	0,2/ m3	0,7/ m3	28%
A.8	18 m3	36	19	1,0/ m3	1,9/ m3	52%
A.9	18,2 m3	204	29	1,5/ m3	11,2/ m3	13%
A.10	18,4 m3	44	20	1,3/ m3	2,3/ m3	56%
D.4	8,9 m3	19	17	1,9/ m3	2,1/ m3	56%
D.5	9,3 m3	11	5	0,5/ m3	1,1/ m3	45%
D.6	9,6 m3	139	99	10,2/ m3	14,4/ m3	70%
D.7	10 m3	25	23	2,2/ m3	2,4/ m3	91%
D.8	10,3 m3	117	73	7,0/ m3	11,3/ m3	61%
D.9	10,6 m3	215	189	17,7/ m3	20,2/ m3	87%
D.10	10,8 m3	192	168	15,4/ m3	17,6/ m3	87,50%
D.11	10,9 m3	189	175	15,9/ m3	17,1/ m3	92,90%
E.1	4,8 m3	10	1	0,2/ m3	2,0/ m3	10%
E.4	5,3 m3	3	3	0,5/ m3	0,5/ m3	100%
E.5	6,1 m3	4	4	0,6/ m3	0,6/ m3	100%
E.7	7,7 m3	62	37	4,7/ m3	7,9/ m3	59%
E.8	8,6 m3	147	115	13,2/ m3	16,9/ m3	78%
E.9	9 m3	75	56	6,1/ m3	8,2/ m3	74%
E.10	9,4 m3	80	74	7,8/ m3	8,4/ m3	92%
E.11	9,6 m3	53	13	1,3/ m3	5,5/ m3	23%
E.12	9,5 m3	11	2	0,2/ m3	1,1/ m3	18%
E.13	7,9 m3	7	1	0,1/ m3	0,8/ m3	12,50%
F.1	4 m3	24	11	2,6/ m3	5,8/ m3	44%
F.2	4 m3	84	38	9,4/ m3	20,9/ m3	44%
F.3	4,3 m3	13	8	1,8/ m3	2,9/ m3	62%
F.4	4,3 m3	29	26	5,9/ m3	6,6/ m3	89%
F.6	4,3 m3	39	19	4,3/ m3	8,9/ m3	48%
F.10	5,4 m3	164	3	0,5/ m3	30/ m3	1,60%
F.12	3,8 m3	40	15	3,9/ m3	10,4/ m3	37,50%
F.13	1,8 m3	60	15	8,2/ m3	33,1/ m3	24,70%
G.4	8,5 m3	141	125	14,5/ m3	16,4/ m3	88%
G.5	9,2 m3	673	633	68/ m3	73/ m3	93%
G.6	7,6 m3	1108	933	121,1/ m3	144,8/ m3	83%
G.7	7 m3	238	193	27,5/ m3	33,9/ m3	81%
G.8	5,5 m3	58	5	0,8/ m3	10,4/ m3	7%
H.2	5,1 m3	19	1	0,19/ m3	3,6/ m3	5%
H.3	5,9 m3	11	8	1,3/ m3	1,8/ m3	72%
H.6	1,7 m3	1	1	0,5/ m3	0,5/ m3	100%
I.5	0,2 m3	224	203	699,7/ m3	772,1/ m3	90%
I.6	0,5 m3	85	83	156,4/ m3	160,2/ m3	97%
I.7	0,1 m3	18	5	29/ m3	104,5/ m3	27%

Fig. 7 Results obtained from the density analysis have been summarized (Diagrams 1–7). The columns labeled “Pottery density per m³” and “total volume excavated” are of particular interest as they emphasize the

important relationship required in order to more accurately define the Mesolithic portion of the cave sequence

crucial point to let us to generate maps of finds frequency and density, based on the different categories of archeological objects described in the final excavation report and associated to the various parcels and units visualized in the original profile drawing. The 3D maps produced were respectively, a map of pottery, harp seal bones, and bone harpoons (Fig. 6).

Pottery analysis

A review of the results indicate an overall trend of diminishing pottery density towards the lower levels of the Stora Förvar cave sequence—despite occasional peaks of increased density in parcels such as D, E, and F (Fig. 7, Diagrams 2, 3, and 4). Over time however, the levels of pottery density eventually decrease with some of the spit units reaching as low levels as 0.8 to 0.1 fragments per unit of volume (m^3). Acting as a deviation to this trend is parcel A (Fig. 7, Diagram 1). According to the original publication from the 1940s, parcel A and B came about as a result of the same parcel being excavated at two separate occasions, and thus it was also divided accordingly. Unfortunately, as it is rather difficult to understand from the original publication as to how this divide was carried out spatially, the strategy was to treat parcel A and B with its artefactual assemblage as one single 3D-reconstructed unit. As such, the results from the density analysis are not entirely reliable as most of the bottom spit units were neglected for analysis, but also because of the necessity to bundle together a majority of the spit units that were labeled A.1-A.4 and A.5-A.6 to name but a few. Another deviant development also occurs in parcel F. The densities of pottery display a somewhat chaotic sequence in which there are two valleys of increase in pottery density throughout the parcel (Fig. 7, Diagram 4). However, what is interesting is the sudden increase that occurs between spit units F.10 and F.13. Ever since spit unit F.4, parcel F had seen a gradual decrease in pottery density that went from almost six fragments per each unit of volume to its very lowest at just half a fragment. However, all of a sudden, the density increases once again. This rather irregular

pattern might very well be explained by the notion that parcel F was excavated at two occasions, in which the excavators dug halfway down into the sequence in parcel F after which excavation of the first couple of spit units in neighboring parcel G began. It is in this specific event that the authors recall how masses of soil had been thrown down from the top of parcel G into the previously excavated parcel F (Schnittger and Rydh 1940, p. 45) and it is thus very likely that this sudden increase is a result of excavators having trampled any pottery remain further down into the parcel causing an accidental intrusion of some of the lower levels. To add support to this hypothesis, one only needs to review the development in the neighboring parcel G. Reviewing the parcel in reverse order, up until spit unit G.8, there is no occurrence of pottery. After spit unit G.8, the density of pottery peaks briefly with a dramatic increase, whereas towards to top it resumes its diminish (Fig. 7, Diagram 5). More importantly, results published by Lindqvist and Possnert (1999) introduced the presence of Early to Late Mesolithic remains within this sequence. Thus, if the neighboring bottom spit units of parcel F were to be contemporary with that of the bottom spit units of parcel G, then the density of pottery should either be very low, or absent altogether as pottery makes its introduction into the Baltic region in the Late Mesolithic (Hallgren 2004, p. 123; Glykou 2014, p. 24).

Parcel H displays an overall low density of pottery per spit unit with layer H.3 amounting to marginally more than a pottery fragment per unit of volume contributing to the general trend of low densities of pottery towards the bottom (Fig. 7, Diagram 6). It should be mentioned once again however that bundled spit units have been neglected, and thus any analysis of spit units “H.4-H.5” has yet to be performed. The final parcel at the very end of the cave is parcel I. Providing us with only three spit units, the pattern is still consistent with previous parcels in which the amount of pottery fragments per unit of volume decreases towards the bottom of the sequence (Fig. 7, Diagram 7).

By using indices of varying pottery densities and results from the osteological analysis (Fig. 8), we argue that additional spit

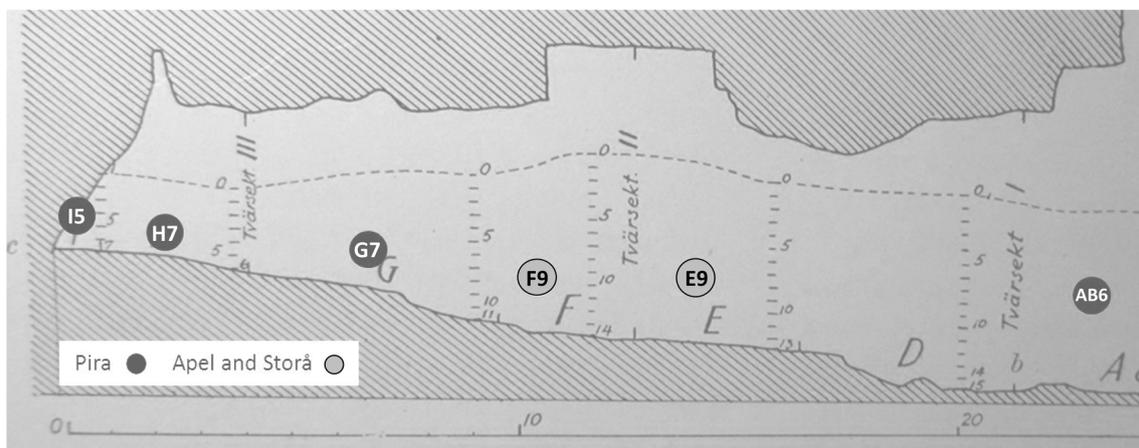


Fig. 8 Section of the cave from north. The dotted line marks the soil surface prior to the excavations. The circles mark the occurrence of bones of harp seal identified by Pira (1926) and Apel and Storå (2017a, b). Scale in meter. Modified from Schnittger and Rydh 1940, Figure 30

units of the Stora Förvar cave sequence may be added to the Early Mesolithic component for further investigation such as radiometric dating and artefactual studies. This inference is built on the idea of groups of hunter-gatherers that either use, or do not use, ceramic technology. For the Early Mesolithic portion, the density of pottery is at a significantly low level that it may very well be ascribed to pioneering groups that precede the Kongemose and Ertebølle cultures. As of yet however, any further analysis as to the cultural affinities of the pottery at Stora Förvar has been made, and so a possibility could be that there is a presence of Ertebølle pottery (or later) in the lowest of levels. Although, this would not be consistent with the numerous AMS-dates from some of the lowest levels of parcel G (Lindqvist and Possnert 1999: Table 2), and thus lends further strength to the idea of intrusion caused by a systematic and arbitrary method of excavation.

Osteological analysis

The osteological analyses of faunal remains have provided additional clues to the relative chronology of the finds from the cave. Early on, the analyses of Adolf Pira (1926) showed that the occurrence of seal species varied in different layers. Bones from Gray seal (*Halichoerus grypus*) and ringed seal (*Phoca hispida*) were most common in the bottom layers of the cave while harp seal (*Phoca groenlandica*) appeared higher up in the stratigraphy (e.g., G7 and H7), from approximately 1.2 m above the bedrock (Fig. 8).

We now know that the oldest layers of the cave date to approximately 9200 cal BP, i.e., the Mesolithic. The oldest use of the cave spans a period of around 1000 years after which there is a hiatus in the stratigraphy when the cave apparently was more or less abandoned between approximately 8200 cal BP to around 6000 cal BP (Apel and Storå 2017a; Apel et al. 2017; Lindqvist and Possnert 1997, 1999).

For the present study, the presence of bones of harp seal may be used as an important chronological indicator together with the pottery. Pira (1929) identified bones of harp seal in

Fig. 10 **a** Distribution of the bone finds in each excavation year and parcel of the cave, weight (g). **b** Distribution of the bone finds in each section and layers of the cave, weight (g). Data from the catalog at the Swedish Historical Museum. Due to the sloping cave floor the same layers do not correspond to the same dates. The borders between the different periods are not to be considered exact (*Dom = finds with bones of domestic animals, apparently younger than c.3000/3500 cal BP, most often though Iron Age/Historical period). **c** Amount of bone finds, total volume, and density of bone finds in combined layers of the cave

the sections and layers I4, G4, I5, G5, B6, H7, and G7 (Fig. 8). A later analysis has confirmed the presence in these layers and added finds in F9 and E7 (Apel and Storå 2017a).

The deepest—and chronologically oldest—occurrences of the harp seal bones roughly coincide with the appearance of a large number of bone harpoons and also fish hooks. Bones of domesticated animals became more common and even more common than seal bones in the uppermost layers which date the Iron Age and Historical period (Ibid.). However, there are some finds of sheep and other domestic animals as deep as G8. The harp seal entered the Baltic basin around 6000 BP cal, i.e., around the time when the hiatus in the cave ends (Bennike et al. 2008; Storå and Ericson 2004).

The identifications of harp seal bones show that the layers associated with the oldest Mesolithic phase were up to 1- to 1.2-m thick at the entrance of the cave, in sections A, D, E, and F but thinner in sections G, H, and I. At the far end of the cave in section I, harp seal bones appear already at c.30 cm above the cave floor.

The estimations of the volume of the layers in each section provide a possibility to evaluate the Mesolithic depositional patterns of bones and, thus, the use of the cave, both horizontally and vertically (Figs. 9 and 11). It has so far been very difficult to investigate the horizontal use of the different parts of the cave.

We here consider the sections inside of the cave and those that date to the Mesolithic. The small amounts of bone finds in section D may be a result of recovery bias. There are some noteworthy differences in the density of bone finds in different layers and sections (Fig. 10). In section D, the lowest layer 12 contained smaller amounts of bone finds than layer 11, after

Fig. 9 C14-dated faunal remains' samples have been georeferenced and put in spatial relation with the 3D model of the cave: **a** sheep 85–225 calAD (5.4%); **b** sheep 55–211 calAD (95.4%); **c** sheep 745–404 calBC (95.4%); **d** ringed seal 7184–7028 calBC (93.2%). They acted as an additional independent chronological indicator to define the boundaries of the Mesolithic portion of the sequence. **e** shows the same portion of the wall cave as it can be observed on site



a

Excavation year	Section A	Section B	Section D	Section E	Section F	Section G	Section H	Section I	Unknown	Total
1888	2412								1834	4246
1889			17943			1299			1823	21065
1890	97590		3304						21623	122517
1891				159067	421902	1264			81500	663733
1892		348595			272989	297695	166637		20515	1106431
1893		24171						106675	504	131350
Various									213785	213785
Total	100002	372766	21247	159067	694891	300258	166637	65437	341584	2263127

b

	Layer	Section A	Section B	Section D	Section E	Section F	Section G	Section H	Section I	Unknown	Total
Historical	Dom*				10445		28			168618	179091
	1		125182		46	29221		16218	173	132	170972
	1-2			1916	217		50				2183
	1-3						205				205
	1-4	3401									3401
	2		142093		96	10577	149	46570	32920	684	233089
	2?									466	466
	2-3						256				256
	3		58113		16	54373	1224	44537	234	5988	164485
	3-4		25				792				817
Iron Age	4		9528	452		4187	47459		16334	5490	83450
	4-5	3324			60						3384
	5		13350	74	24548	15929	76888		24575	828	156192
	5-6	124			112						236
	5-8									27	27
	6	1865	9764	1412	2117	30383	33877	34773	234	145	114570
	6?				21		4				25
	6-7			148		650					798
	6-8	117									117
	7	253	451	224	2988	14449	16580	22606	32205	118	89874
7-8	1020		726	103						1849	
8	13	445	1234		14948	27657	1394			45691	
8-9	17		390	33						440	
Neolithic/ Mesolithic upper?	9	1177	114	1246	6735	74921	36452			529	121174
	9-10	263		813	15						1091
	10	28739	6462	2356	4568	138854	42367				223346
	10-11	1428		2350		118					3896
	10-12	105		22							127
	11	17492	6935	3246	21630	107264	16198			21	172786
	11?					39852					39852
Mesolithic upper	11-12			606							606
	12	36756		777	69237	47357		94		1	154222
	12-	1140									1140
	12?					3					3
	12-14	328									328
	13				2819	25351				132	28302
	13-14	266		249							515
	14-15			29							29
	15			1092						313	1405
	Unknown	2174	304	1885	13261	86454	72	445		158092	262687
Total	100002	372766	21247	159067	694891	300258	166637	106675	341584	2263127	

c

	Weight (g)	Volume, m ³	Mean weight (g)/m ³
Historical/Iron Age/Bronze Age/Neolithic	997991	239	4176
Neolithic/Mesolithic upper?	169647	186	912
Mesolithic Upper	646858	141	4588
Mesolithic lower	185944	96	1937
Unknown	262687	662	397
All	2263127	662	3419

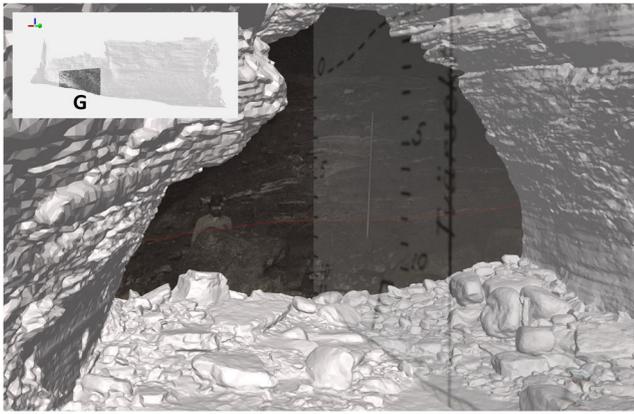


Fig. 11 View of profile of section G, from west after it has been properly georeferenced in the 3D cave model. The change in the character of the stratigraphy, marked by an arrow, slightly below the shoulders of the standing man probably marks the hiatus, i.e., a soil surface layer when the cave apparently was not in use for around 1000 years. Reproduced with permission by the Antiquarian Topographical Archives, Stockholm (Photo 1492:2)

which, the find density decreases higher up in the stratigraphy. A similar pattern may be seen in sections E and F, although the deposits with higher amounts of finds are thicker in section F. This could reflect a difference in soil cover in the front end of the cave and at the end of the cave. Thus, the bones could have been deposited on an existing soil cover at the entrance of the cave. Section G and also H and I exhibit the highest densities of finds in the layers immediately on top of the bedrock (floor).

Considerably, larger amounts of finds were deposited in the Mesolithic layers in sections G and F compared to sections D and E. Possibly, the areas at the entrance of the cave, which actually had large floor areas, were kept cleaner from refuse of the seals. There is a marked difference in the floor areas between the layers and sections.

Thus, the absolute amounts of bone finds are highest in the central part of the cave, but the density of bone finds is actually higher at the end of the cave, and lowest at the entrance. Indeed,

we discern a Mesolithic depositional pattern to deposit the refuse after the hunted seals. Noteworthy in the comparison is also the drop in density of finds in layers 8 in sections F and G. These layers probably belong to the end of the Mesolithic, at the time of the hiatus in the occupation. It seems that the intensity of deposition, as seen in smaller mean amounts of bone per m^3 , decreased through time, possibly in the period prior to the abandonment of the cave. This change in depositional patterns is also associated to changes in seal hunting patterns (Apel and Storå 2017a, b).

To summarize, some elements are particularly worth of attention as they provide information in terms of relative and absolute chronology, useful to trace and define certain spatial boundaries. In particular:

- Density values of pottery and faunal remains act as chronological indicators to define the temporal boundaries of the Mesolithic phase of inhabitation of the cave. Most importantly, they provide a *terminus* that here can be marked to spatially define the volume of the sequence characterized by Mesolithic and post-Mesolithic events. In this respect, the presence of harp seal, which entered the Baltic basin around 6000 Cal BP, is another good chronological indicator to be considered.
- More traces indicate the uppermost boundary of the Mesolithic portion of the sequence and they can be observed in a historical picture of the profile of section G which is recognizable by the dark color of the soil matrix. The possibility of georeferencing the picture let us to put in connection the visible hiatus in turn with the volumetric model of parcel G, the digitized hand-made profile drawing and the 3D model of the cave (Fig. 11).
- In terms of absolute chronology, further indication about the spatial pattern related to the Mesolithic phases of the cave is provided by the $c14$ -dated faunal remains from wall concretions, which have been georeferenced and put in spatial connection with the above-mentioned datasets (Fig. 9).

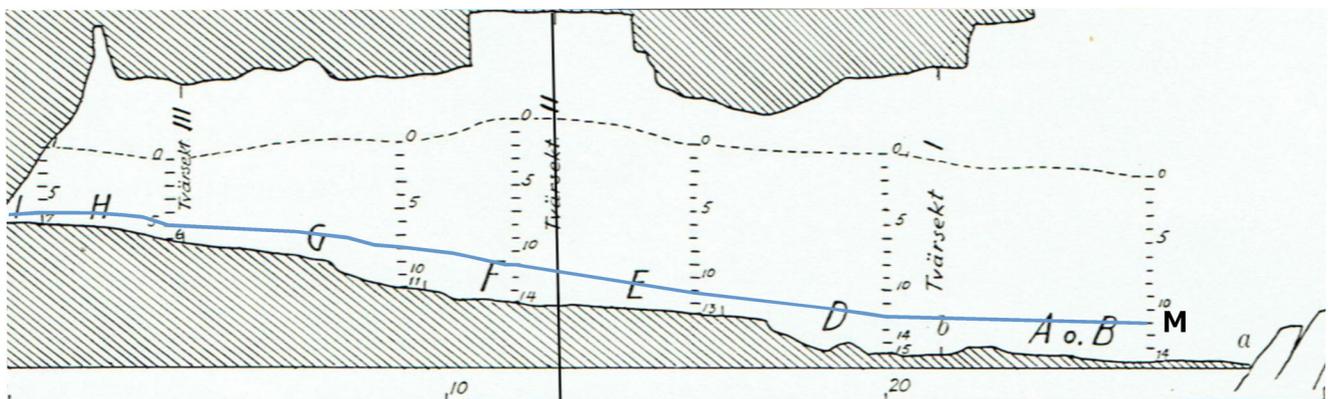


Fig. 12 Interpretative line (M) illustrating the uppermost boundary of the Mesolithic phase of Stora Förvar cave. Such interpretation comes as a result from the combination of different independent chronological indicators, that include: $c14$ -dated faunal remains from wall

concretions; 3D density maps for pottery finds, harp seal bones and harpoons, identification of a clear stratigraphic boundary visible on the section of parcel G within a georeferenced historical picture

Conclusions

This contribution has sought to demonstrate how the integrated combination of digital methods can significantly improve the interpretative framework of a Prehistoric sequence. In particular, advanced 3D GIS functions together with legacy data provided the opportunity to partially re-contextualize archeological finds belonging to the Prehistoric cave of Stora Förvar and to take advantage of the digitally reconstructed sequence of arbitrary layers to quantitatively assess the distribution of several classes of artifacts in order to detect patterns associated to the different phases of cave inhabitation. Noteworthy is the study of those categories of artifacts which act as important indicators for the chronology of the layers. Having those artifacts represented as a numerical attribute linked to the volumetric model of the sequence allowed to create 3D maps that could visually represent the distribution of each class based on values of frequency and, more importantly, on the density as a result from the relation between each layer's volume and number of finds. The emerging patterns have been thus put in relation to other datasets consisting of legacy data that had been properly georeferenced in order to contextualize their contents. Besides being an attempt of promoting a "heuristic" usage of three-dimensionality in the context of a site investigation, this combined approach allowed archeologists to answer some questions related to the site, which could not have been addressed without a spatial analysis of the original layers.

As a final result of the analysis, an interpretative line can be traced in order to highlight the chronological boundaries of such phases (Fig. 12).

Nonetheless, some biases must be taken into account, as there are several issues that influence the original position of the finds and so, any possible interpretation. First of all, the excavation techniques employed, consisting of arbitrary layers, by definition do not follow the actual stratigraphy made up of natural and anthropic layers as they deposited. It is very likely that the same spit unit contains more original stratigraphic layers which correspond to different chronological phases in the cave. Additionally, some inaccuracy in the documentation process did not allow to properly link all the finds to their original unit, making the reconstruction of the 3D maps more uncertain, especially in parcels A and B, which do not even have clear boundaries on their uppermost layers, as they were originally located just outside the entrance of the cave. To sum up, the approach as it has been illustrated demonstrates the key role three-dimensionality that plays in enabling to understand an archeological stratigraphy. Combining relative and absolute chronological indicators in a same georeferenced space can enormously contribute to define areas of artifacts' accumulation and to understand the way the anthropic actions affected the making of the observed deposits so as to identify different phases of inhabitation of the cave. Such information is an important premise not only to improve our understanding of the

single site on a local level, in broader terms, but also to expand our knowledge about the pioneer settlement of Gotland. In a broader perspective, a similar workflow can be extended to countless case studies in which archeological documentation has been produced in pre-digital era and used to build an interpretation of the site. Any previous study can thus be revised and possibly improved by giving a spatial dimension to features and objects that had been already examined by taking into account of their vertical position and their temporal relation with the space. Indeed, the possibility of collecting the data in a geodatabase would allow more scholars to integrate further information into the system so as to integrate additional elements that can be used in support of site interpretation. Further research needs to be conducted in order to cope with issues concerning data integrity and consistency especially in relation to the material derived from archival source, for which a bit more of uncertainty characterize the act of data collecting. Nonetheless the results obtained seem to foster this approach and to mark a significant advance in the practice of data-reuse which will be beneficial to the reinterpretation of many spatially and temporally diverse archeological contexts.

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References

- Apel J, Storå J (2017a) The Pioneer settlements of Gotland: a behavioural ecology approach. The ecology of early settlement in northern Europe - conditions for subsistence and survival (Volume 1). Equinox eBooks Publishing, United Kingdom. Dec 2017. ISBN 9781781795156
- Apel J, Storå J (2017b) Ett återbesök i Stora Förvar och en ny bild av mesolitikum på Gotland. Arkeologi på Gotland 2. Tillbakablickar och nya forskningsrön. Institutionen för arkeologi och antik historia, Uppsala Universitet & Gotlands Museum. Uppsala och Visby
- Apel J, Storå J, Landeschi G (2015) Ett återbesök i Stora Förvar. Efterundersökning av stenålderslokalen Stora Förvar, Stora Karlsö, Eksta sn, RAÄ 138:1, Gotland. Rapport arkeologisk undersökning. Lunds Universitet. Lund
- Apel J, Wallin P, Storå J, Possnert G (2017) Early Holocene human population events on the island of Gotland in the Baltic Sea (9200–3800 cal. BP). *Quaternary International*, available on-line 28 March 2017

- Bennike O, Rasmussen P, Aaris-Sørensen K (2008) The harp seal (*Phoca groenlandica* Erxleben) in Denmark, southern Scandinavia, during the Holocene. *Boreas* 37:263–272
- Beraldin JA, Blais F, Cournoyer L, Picard M, Gamache D, Valzano V, Bandiera A, Gorgoglione M (2006) Multi-resolution digital 3D imaging system applied to the recording of grotto sites: the case of the grotta dei cervi. In proceedings of the 7th international conference on virtual reality, archaeology and intelligent cultural heritage, 45–52. Eurographics Association
- Berggren Å, Dell'Unto N, Forte M, Haddow S, Hodder I, Issavi J, Lercari N, Mazzuccato C, Mickel A, Taylor J (2015) Revisiting reflexive archaeology at Çatalhöyük: integrating digital and 3D technologies at the trowel's edge. *Antiquity* 89:433–448
- Callieri M, Dell'Unto N, Dellepiane M, Scopigno R, Soderberg B, Larsson L (2011) Documentation and interpretation of an archaeological excavation: an experience with dense stereo reconstruction tools. In VAST The 11th International Symposium on Virtual Reality Archaeology and Cultural Heritage, 33–40. Eurographics
- Campana S (2014) 3D modeling in archaeology and cultural heritage – theory and best practice. In: Campana S, Remondino F (eds) 3D surveying and modeling in archaeology and cultural heritage theory and best practices. BAR international series, Oxford, pp 151–158
- Campanaro DM, Landeschi G, Dell'Unto N, Leander Touati A-M (2015) 3D GIS for cultural heritage restoration: a 'white box' workflow. *J Cult Herit*, 18, 321–332. Elsevier
- Cignoni P, Callieri M, Corsini M, Dellepiane M, Ganovelli F, Ranzuglia G (2008) Meshlab: an open-source mesh processing tool. In Eurographics Italian chapter conference (Vol. 2008, pp. 129–136)
- De Reu J, Plets G, Verhoeven G, Bats M, Cherretté B, De Maeyer W, De Smedt P, Deconynck J, Herremans D, Laloo P, Van Meirvenne M, De Clercq W (2013) Towards a three-dimensional cost-effective registration of the archaeological heritage. *J Archaeol Sci* 40(2): 1108–1121
- De Reu J, De Smedt P, Herremans D, Van Meirvenne M, Laloo P, De Clercq W (2014) On introducing an image-based 3D reconstruction method in archaeological excavation practice. *J Archaeol Sci* 41: 251–262
- Dell'Unto N (2014) The use of 3D models for intra-site investigation in archaeology. In: Campana S, Remondino F (eds) 3D surveying and modeling in archaeology and cultural heritage theory and best practices. BAR international series, Oxford, pp 151–158
- Dell'Unto N, Landeschi G, Leander Touati A-M, Dellepiane M, Callieri M, Ferdani D (2015) Experiencing ancient buildings from a 3D GIS perspective: a case drawn from the Swedish Pompeii Project. *J Archaeol Method Theory*, 23, 73–94. Plenum Press
- Dellepiane M, Dell'Unto N, Callieri M, Lindgren S, Scopigno R (2012) Archeological excavation monitoring using dense stereo matching techniques. *J Cult Herit* 14:201–210
- ESRI (2014) Import 3D files. Available at: [http://resources.arcgis.com/EN/HELP/MAIN/10.2/index.html#/Import_3D_Files/00q900000970000000/](http://resources.arcgis.com/EN/HELP/MAIN/10.2/index.html#/Import_3D_Files/00q90000097000000/) (Accessed 22 June 2016)
- ESRI (2015) GIS Tutorial 10 - ArcGIS 3D Analyst. Available at: http://downloads2.esri.com/ESRIpress/images/144/GISTutorial_samplechapter.pdf. (Accessed 22 June 2016)
- Forte M, Dell'Unto N, Issavi J, Onsurez L, Lercari N (2012) 3D archaeology at Çatalhöyük. *International Journal of Heritage in the Digital Era* 1(3):351–378
- Frischer B (2008) From digital illustration to digital heuristics. In: Frischer B, Dakouri-Hild A (eds) Beyond illustration. 2D and 3D digital technologies as tools for discovery in archaeology. BAR International Series 1805, Oxford, pp 5–24
- Galeazzi F, Moyes H (2011) 3D documentation in archaeology: recording Las Cuevas site, Chiquibul Reserve, Belize. In CAA 2012
- Galeazzi F, Moyes H, Aldenderfer M (2014) Defining best 3D practices in archaeology: comparing laser scanning and dense stereo matching techniques for 3D Intrasite data recording. *Adv Archaeol Pract* 2(4): 353–365
- Gillings M, Goodrick GT (1996) Sensuous and reflexive GIS: exploring visualization and VRML. *Internet Archaeology*, 1. Available at: http://intarch.ac.uk/journal/issue1/gillings_index.html. (Accessed 22 June 2016)
- Glykou A (2014) Late Mesolithic - Early Neolithic Sealers: a case study on the exploitation of marine resources during the Mesolithic-Neolithic transition in the south-western Baltic Sea. In: R. Fernandes, and J. Meadows, eds. Human Exploitation of Aquatic Landscapes. Special issue. *Internet Archaeology* [online], 37. Available from: <https://doi.org/10.11141/ia.37.7>
- Hallgren F (2004) The introduction of ceramic technology around the Baltic Sea in the 6th millennium. In: Knutsson, H. Coast To Coast - Arrival: Results And Reflections: Proceedings Of The Final Coast To Coast Conference, 1–5 October 2002 In Falköping, Sweden, Uppsala: Coast to Coast Project, Department of Archaeology and Ancient History
- Herrmann N (2002) GIS applied to bioarchaeology: an example from the Rio Talgua caves in Northeast Honduras. *Journal of Cave and Karst Studies* 64(1):17–22
- Hiscock P (1985) The need for a taphonomic perspective in stone artefact analysis. *Queensland Archaeological Research* 2:82–97
- Hodder I (2000) Developing a reflexive method in archaeology. In Hodder, I. (ed.) *Towards reflexive method in archaeology: the example at Çatalhöyük*. McDonald Institute for Archaeological Research, Cambridge. (3–14)
- Hughes PJ, Lampert RJ (1977) Occupational disturbance and types of archaeological deposit. *J Archaeol Sci* 4(2):135–140
- Katsianis M, Spyros T, Kotsakisa K, Kousoulakoub A (2008) A 3D digital workflow for archaeological intra-site research using GIS. *J Archaeol Sci* 35:655–667
- Landeschi G, Dell'Unto N, Ferdani D, Leander Touati A-M, Lindgren S (2015) Enhanced 3D-GIS: documenting insula V 1 in Pompeii. In Giligny, F., Djindjian, F., Costa, L., Moscati, P. and Robert, S. (Eds.), *Proceedings of the 42nd conference on computer applications and quantitative methods in archaeology – Paris 22nd to 25th April* (pp. 349–360). Oxford: Archaeopress
- Landeschi G, Nilsson B, Dell'Unto N (2016a) Assessing the damage of an archaeological site: new contributions from the combination of Image-based 3D modelling techniques and GIS. *J Archaeol Sci Rep* 10:431–440 10 p
- Landeschi G, Dell'Unto N, Lundqvist K, Ferdani D, Campanaro DM, Leander Touati A-M (2016b) 3D-GIS as a platform for visual analysis: investigating a Pompeian house. *J Archaeol Sci*, 65, 103–113. Academic Press
- Landeschi G, Apel J, Lindgren S, Dell'Unto N (2018) An exploratory use of 3D for investigating a prehistoric stratigraphic sequence. *Proceedings of the 44th Computer Applications and Quantitative Methods in Archaeology Conference, CAA 2016 Oslo, 29 March–2 April 2016*
- Lantmateriet (2015) Lantmateriet 2015. Available at: <https://www.lantmateriet.se/globalassets/om-lantmateriet/om-oss/dokument/2016/webb.160222.lm.verksamhetberattelse.2015.pdf>. (Accessed 22 June 2016)
- Lerma JL, Navarro S, Cabrelles M, Villaverde V (2010) Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the upper Palaeolithic cave of Parpalló as a case study. *J Archaeol Sci* 37(3):499–507
- Lindqvist C, Possnert G (1997) The subsistence economy and diet at Jakobs/Ajvide, Eksta parish and other prehistoric dwellings and burial sites on Gotland in long-term perspective. In: Burenhult, G. (ed), *Remote sensing vol 1. These and papers in north-European archaeology* 13a. Stockholm
- Lindqvist C, Possnert G (1999) The first seal hunter families on Gotland. On the Mesolithic occupation of the Stora Förvar cave. *Current Swedish Archaeology* 7:65–88

- Lundström V (2016) Exploring new horizons through the use of legacy data. An innovative approach for assessing the early mesolithic chronology at the cave site Stora Förvar using 3D-GIS and density analysis. M.A. Thesis Archaeology. Lund University. (unpublished)
- Moyes H (2002) The use of GIS in the spatial analysis of an archaeological cave site. *Journal of Cave and Karst Studies* 64(1):9–16
- Müllerova J, Szabo P, Kopecky M, et al. (2013) LONGWOOD - integrating woodland history and ecology in a geodatabase through an interdisciplinary approach. First international conference on remote sensing and Geoinformation of the environment (Rscy2013). Volume: 8795
- Nekhrizov G, Tzvetkova J, Kecheva N (2012) Archaeological GIS: Kazanlak surface survey in 2009-201. In Proceedings of the First European SCGIS Conference “Best practices: Application of GIS technologies for conservation of natural and cultural heritage sites” 21–23 May 2012, Sofia, Bulgaria, (pp. 53-62). Available at: http://proc.scgis.scgisbg.org/S2-1_Nekhrizov.pdf. (Accessed 10 March 2016)
- Opitz R, Nowlin J (2012) Photogrammetric modeling + GIS: Better methods for working with mesh data. Available at: <http://www.esri.com/news/arcuser/0312/photogrammetric-modeling-plus-gis.html> (Accessed 12 July 2016)
- Pira G (1926) On bone deposits in the cave Stora Förvar on the isle of Stora Karlsö, Sweden *Acta Zoologica* 7
- Puchol OG, McClure SB, Senabre JB, Villa FC, Porcelli V (2013) Increasing contextual information by merging existing archaeological data with state of the art laser scanning in the prehistoric funerary deposit of Pastora cave, eastern Spain. *J Archaeol Sci* 40(3):1593–1601
- Schnittger B, Rydh H (1940) Grottan Stora Förvar på Stora Karlsö. Wahlström & Widstrand, Uppsala
- Schnittger B, Rydh H, Kolmodin L, Stolpe H (1940) Grottan Stora Stora Storlösa Stora Karlsö: investigated by Lars Kolmodin and Hjalmar Stolpe. Described by Brother Schnittger and Hanna Rydh. Wahlström & Widstrand
- Storå J, Ericson PGP (2004) A prehistoric breeding population of harp seals (*Phoca groenlandica*) in the Baltic Sea. *Marine Mammal Science* 20(1):115–133 (January 2004)
- Tennant EW (2007) A sample Geodatabase structure for managing archaeological data and resources with ArcGIS. *Technical Briefs in Historical Archaeology* 2:12–23
- Van Ruymbekke M, Carré C, Delfosse V, Pfeiffer M, Billen R (2015) Towards an archaeological information system: improving the Core data model. In: Giligny F, Djindjian F, Costa L, Moscati P, Robert S (eds) CAA 2014 21st century archaeology: concepts methods and tools: proceedings of the 42nd annual conference on computer applications and quantitative methods in archaeology. Archaeopress, Oxford, pp 245–253
- Wilhelmson H, Dell’Unto N (2015) Virtual taphonomy: a new method integrating excavation and post-processing of human remains. *Am J Phys Anthropol* 157:305–321