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An evaluation of the visualisation and interpretive potential of applying GIS data processing techniques to 3D rock art data

Christian Horn[a,*], Derek Pitman[b], Rich Potter[c]

[a] Gothenburg University, Box 200, 405 30 Gothenburg, Sweden
[b] Bournemouth University, Fern Barrow, Poole, Dorset BH 12 5B, United Kingdom
[c] Gothenburg University, Sweden

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ABSTRACT

Rock art provides a tangible visual link to past communities and has significant value in building our understanding of prehistoric societies. Its recording and interpretation has long provided a window to intangible aspects of society, such as belief systems and folk narratives. Petroglyphic rock art has traditionally been recorded through simple rubbing, or frottage, and the majority of interpretations and narratives to date have been based on this work. Recently, three-dimensional capture techniques have become readily available and they replace traditional approaches to rock art recording. These techniques are valuable, but the data-heavy outputs lack the interpretive clarity of traditional methods. This paper explores these issues through a novel approach that employs topographic landscape analysis techniques, initially developed for LiDAR processing, to produce clear images that have the precision and dimensional accuracy of 3D captured data, but the visual clarity of traditional methods. Specifically, this paper outlines an approach based on local relief modelling (a technique that highlights subtle topographic features) and explores its efficacy through case studies of Bronze Age Scandinavian petroglyphs. This method was developed to aid the analysis of 3D models and to improve visualising the results based on such investigations. This work offers a significant impact on rock art studies as it facilitates the identification of previously unidentified motifs, and allows a clearer sense of petroglyphic world views. The technique can be applied to models of other archaeological surfaces.

1. Introduction

This paper outlines a method for the visualisation and interpretation of petroglyph data using a case study from Bronze Age Scandinavia. Rock art can be seen as a tangible way in which past human communities ‘socialised landscapes’, leaving a mark visible through pigment or, in this case, through petroglyphs, which gives a long lasting glimpse into aspects of society that are often lost to archaeology (Chippindale and Taçon, 1998). Its record and analysis are a vital component for understanding past social dynamics, organisation, and character. The methodological refinement of recording, analytical techniques, and the presentation of accurate and precise graphical reproductions is a fundamental field of research.

Within the context of Scandinavian rock art study, documentation techniques have been developed and refined over the last 150 years in an attempt to produce graphic representations of incised rock art that best represent the original work. These developments went through various imaging techniques from Indian ink graphics, drawings using measurement grids, tracings, and rubbings (frottage). Recently, the Swedish Rock Art Research Archive (SHFA), which is concerned with the documentation and research of Scandinavian rock art, has advocated the use of 3D models as a new, complimentary documentation standard (Horn et al., 2018). Bertilsson and others have argued that 3D models based on image-based and range-based modelling techniques are a way to minimize bias and improve the quality of documentation (Bertilsson, 2015; Bertilsson et al., 2017; Horn et al., 2018; Rondini, 2018). The research using 3D documentation has demonstrated the veracity of Nordbladh's, 1981 argument that high-quality rock art research requires high-quality documentation (Nordbladh, 1981), through new discoveries and a reinvigorated debate about rock art documentation (Díaz-Andreu et al., 2006; Díaz-Guardamino Uribe and Wheatley, 2013; Fahlander, 2017; Ling and Bertilsson, 2017; Rondini, 2018).

Central to the development of this field has been the shrinking size/cost of laser scanners and the development of multi-image photogrammetry (using software like Agisoft Photoscan©; now

* Corresponding author.
E-mail addresses: christian.horn@gu.se (C. Horn), dpitman@bournemouth.ac.uk (D. Pitman), richard.potter@gu.se (R. Potter).

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Metashape©). This has greatly facilitated accessible and versatile use of 3D documentation of rock art research. Precise and accurate data capture of rock art is significant, but it is vital to be able to interrogate the data and show the results of the analysis of 3D data to the public in a readable, understandable format (see Reu et al., 2013). Typically, traditional techniques like rubbing or tracing documentations provide a visibly clear and understandable image, despite their clear shortcomings. Similarly, journals are increasingly offering the ability to upload models, and 3D hosting sites such as sketchfab.com enable the curation and distribution of rock art documentation.

It is essential then, that data resulting from the capture of three dimensional rock art can be processed, curated, and distributed in a visually clear and accessible manner. However, file size restrictions, necessary computer power, and technical knowhow limit these opportunities and the impact of such digital dissemination. Consequently, it is of significant value to replicate the positive aspects of traditional documentation with the advantages of digital data capture. This paper proposes a relatively straightforward method for the transformation of 3D data into easily discernible and distributable visualizations of complex 3D datasets. The images exhibit the clarity of rubbings (also termed frottage), but retain the accuracy of the 3D recording. This creates visually clear and accessible images that show topographic characteristics of engraved rock art, as well as potentially highlighting previously unidentified imagery. In this article, various tentative interpretations will be given when discussing the advantages of this visualisation method. A fuller argument to sustain such interpretations requires more than one example and a much deeper discussion. This would distract from the main issue of this article, i.e. the method. Some cases have been discussed in detail, and the published or in print contributions will be referenced appropriately.

This work has been conducted for the purpose of finding a better way to visualise the carvings for a later study using an Artificial Intelligence approach within the project "Rock Art in three Dimensions" granted by the Swedish National Bank's Jubileefond (Riksbankens Jubileumsfond; Ref.nr. IN18-0557:1). The purpose is to further the systematic digital documentation of the UNESCO World Heritage Area in Tanum using holistic, less biased methods. The sites for this study were the first that were documented using either photogrammetry or laser scanning. They were chosen to show that both methods of acquiring 3D models could be used.

2. Incised rock art

A study in the production techniques of petroglyphs conducted by G. Burenhult demonstrated that they typically occur from the following actions: carving, incision, grinding, and through percussive actions. The latter is the most prevalent for of rock art, while true carvings and incisions usually only occur from the Iron Age onwards and are most frequent during the Viking Age (Burenhult, 1980). Percussive techniques were mostly used to apply petroglyphs during prehistory in Scandinavia, but they are also found on the Iberian Peninsula, the British Isles, and the Alpine rock art regions. The most common form of rock art is cupmarks, which are half-spherical depressions in the rock (Horn, 2016). Apart from such abstract motifs, there are figurative petroglyphs, most of which depict canoes, anthropomorphs, metalwork, and animals (Goldhahn and Ling, 2013; Nimura, 2015). Many other motifs such as footsoles, sun discs, wagons, aards, etc. also exist (Bertilsson, 1987; Malmer, 1981; Skoglund, 2013). In the majority of cases Scandinavian petroglyphs are applied to exposed bedrock outcrops, so called panels. Petroglyphs were also made on loose boulders, especially in Denmark and Northern Germany, but also in Sweden and Norway. In this form, they most often occur in burial contexts such as the famous barrows from Kivik and Sagaholm in Sweden (Capelle, 1972, 2008; Glob, 1969; Goldhahn, 1999, 2009, 2016). Scandinavian rock art is the biggest source of pictorial evidence for Bronze Age life, society, and belief systems. Beyond Scandinavia the petroglyphs may have wider implications for the European Bronze Age.

3. Rock art documentation

3.1. Traditional recording techniques

Most rock art in Scandinavia is so shallow that it is difficult to identify visually. Therefore, depth is a crucial aspect of any documentation of petroglyphs; traditional methods make use of this dimension to document rock art. Rubbing, for example, only works because less graphite is applied to the paper over carved depressions. Their advantages and disadvantages have been described in detail elsewhere (Horn et al., 2018; Nordbladh, 1981; Rondini, 2018) so only a brief outline will be presented here. The main methods used were night photography, tracing, and rubbing (frottage). In night photography an artificial light source is taken to the petroglyph panel and shone at an oblique angle during evenings and nights when there is no sunlight. This creates sharp shadows even from small irregularities in the rock, and thus makes petroglyphs visible. Tracing involves a tactile examination of the rock's surface searching for depressions. Each find is interpreted either as artificial, natural, or damage based on the experience of the documenter. Afterwards, the appropriate lines are painted using chalk paint. Following this step, large plastic sheets are fixed to the rock and the lines are transferred. For rubbings, large sheets of paper are fixed to a panel, which in many cases had been pre-examined with a tactile survey. This paper is rubbed using a sponge and graphite. Where the paper lies over depressions in the rock, less pigments are deposited. These areas show up lighter in colour on the paper.

All three methods are long-standing methods in rock art documentation, and the critical comments raised here and elsewhere do not deny their usefulness or that they are able to convey important information. However, to be able to include rock art documentation into research in a scientific manner and assess its relevance, it is necessary to understand the methods shortcomings. None of the techniques described are reductive as they do not record the third dimension of rock art. Many steps of inference are necessary to document petroglyphs using tracings and rubbings; as such, recorder bias is inherent to the documentation process (Bertilsson et al., 2017; Horn et al., 2018). Rubbings and tracings pose a risk to the panels due to the extended periods of time that the documenters spend on the rock. All three methods create problems with spatial relationships. The various angles from which photos are taken skew motifs and make the outcome unusable for measurements of dimensions and distances. The paper or plastic sheet of both other methods are stretched out over the curvature of the rock, but are later flattened out which distorts the real-world position of motifs (Nordbladh, 1981).

3.2. Three-dimensional rock art documentation

The capture of three dimensional data is of significant value within archaeology and heritage (Alexander et al., 2015; Ioannides and Quak, 2014; Molloy, 2018). From landscape survey to artefact analysis, the ability to digitally capture three-dimensional data on a range of scales has facilitated a rapid increase in the ability to share and disseminate information. Projects such as the facial reconstruction of the Cheddar Man have successfully shared 3D scans of skeletal material among research teams to great effect (Lotzof, 2018). The rapid uptake has led to significant epistemological leaps in the way in which data can be captured, used, and disseminated (Karasik and Smilansky, 2008; Molloy, 2018). In broad terms, there are two types of 3D data capture; image base and range based modelling. Image based modelling uses multiple static images and pixel recognition to generate three-dimensional point clouds, range based modelling uses 'time of flight' principles to establish point clouds in relation to a laser source and receiver (Skarlatos and Kiparissi, 2012). The accuracy and level of detail achievable through these techniques is far beyond that of non-digital documentation. In recent years, the cost reduction in computing power and better accessibility to software has lowered the barrier against using them considerably. As a result, these techniques have become increasingly important for the documentation of rock art in many regions since the 2000s (Alexander et al., 2015; Barnett et al., 2005; Díaz-Guardamino Uribe and Wheatley, 2013; Lerma et al., 2010; Lerma et al., 2013; Meijer, 2016; Reu et al., 2013).

These digital capture techniques are central to the case study presented here which focuses on the UNESCO world heritage area in Tanum, Sweden (Horn et al., 2018). Photogrammetric documentation is achieved through a combination of Structure from Motion with subsequent dense Multi-Stereo View (Bertilsson et al., 2014; Bertilsson, 2015; Bertilsson et al., 2017; Meijer, 2016; Sevara and Goldhahn, 2011). For range-based modelling, the SHFA uses a Handyscan 700™ red-light laser scanner with a maximum resolution of 0.05 mm.

The biggest advantage of image-based and range-based modelling is their capability to record, and thus, preserve all three dimensions of petroglyphs. The possibility to turn and adjust the viewing angle as well as the lighting in the 3D models is a great advantage for researchers, because it offers opportunities to study the panels in ways unavailable in the field. Everything on the panel that is within the technical capacity of the chosen method is recorded. No human decision is necessary, and the documentation cannot be intensified on some parts of the panel and lacklustre in others. Thus, bias in capture is reduced by a considerable degree, although it certainly still exists in the interpretation of the 3D data.

3.3. Problems encountered with 3D documentation

All 3D data requires visualisation to convey its content for investigation, interpretation, and dissemination. In archaeology, visualisation is rarely discussed explicitly beyond practical concerns, and is considerably less theorized (Reilly, 1989). Green (1998) discusses the need for the proper visualisation of complex data such as 3D models, and highlights the need to integrate theories of computer graphics and human perception. Jacques Bertin's (1983) 'image theory' is, to date, the most advanced theoretical framework as it considers human cognition to be an element of visual interpretation. He identifies the problem that the human eye can only represent two dimensions in the retinal image, which means that our brains make a 2D image out of 3D reality. To perceive 3D shapes, humans need multiple combined cues (Welchman et al., 2005). Therefore, observations of a 3D model are aided to a considerable degree by the motion of the model and lighting across the surface as this provides the visual cues needed to perceive its shape. As soon as the model is static, perception of its dimensions becomes problematic. For example, screenshots used in the majority of publications lose many subtle differences in shape and depth. It is therefore difficult to show all of the details in one screenshot.

The lighting example of the model of panel 184:1 in Finntorp, from the south-east, conceals parts of a boat in the right top corner (Fig. 1a) and lighting it from the south makes some of the humans and upper boats problematic to recognize (Fig. 1b). Given the limited number of illustrations most journals allow, it is not possible to demonstrate all lighting positions and configurations.

Publishing 3D models directly may remedy that, but their file sizes make this problematic. Professional accounts, for example, on the 3D model hosting website Sketchfab©, currently only allow models up to 500 MB. While this may change in the future, larger models (1GB+) still require more computing power to load and move the model, making them not available to everyone. Most full site documentations prepared by the SHFA exceed the limit of 500 MB, and most are even larger than 1GB (Table 1). Additionally, hosting larger file sizes in the future will likely merit considerable costs which many projects may struggle to bear. These constraints mean that models must often be decimated, which carries the risk of losing important details. Lastly, using software like Meshlab© for viewing, rotating, and lighting models requires technical skill which potentially restricts their non-specialist use.

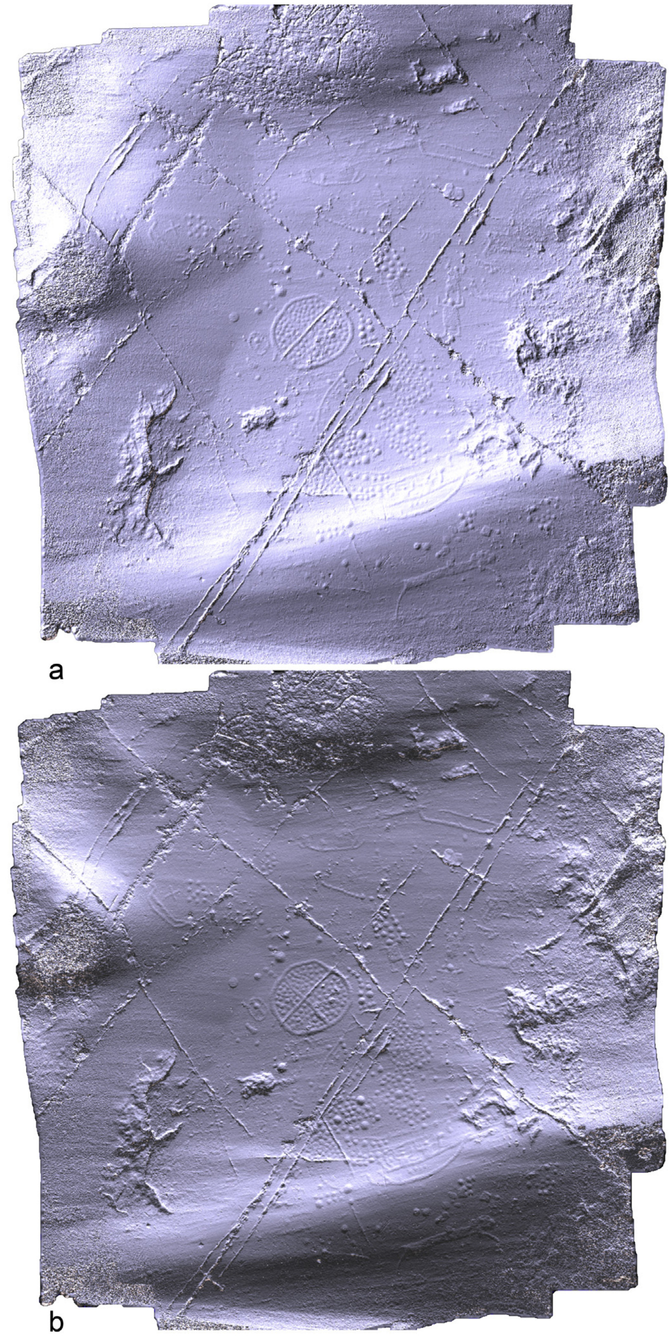

Fig. 1. Snapshots taken in Meshlab from a 3D model (photogrammetry) of a rock art panel in Finntorp, Sweden (RAÄ Tanum 184:1) with lighting from the south-east (a) and the south (b). The extend of the engraved surface is 480 × 400 cm.

3.4. Digital decision making: interpretation versus curation of rock art panels

The interpretation of rock art panels inevitably requires the use of human knowledge and understanding. However, the curatorial process of digital rock art representations should strive to present as little human bias as possible. There are a suite of tools for "highlighting" the images on panels, but we argue here that there is a difference between

Table 1
Summary of the extent of the panels and the file sizes in MB for the 3D model, the geotiff, and as output.

	Finntorp 95:1	Finntorp 184:1	Hoghem 160:1	Gryt 1:1	Tanum 311:1	Fossum 255:1	Tanum 198:1
Extent (cm)	250x120	480x400	880x250	830x320	900x600	1300x500	1400x500
Sqm.	3	19,2	22	26,6	54	65	70
3D model file size (MB)	602	510	721	1010	1620	2800	3860
ArcGIS as .tiff (600 dpi; MB)	27,1	32,4	19,3	10,9	19,1	20,5	24,1
Output saved as .png	20,1	23,3	12,7	5	10,3		16,3

enhancing the topographic features of the panel and superimposing what the researcher wants to be shown. The latter is essential in interpretive discussion, but of less value in the presentation and curation of raw data. Tools like Meshlab are useful, especially for smaller panels without a strong global curvature and sections of larger panels where rendering options such as Radiance Scaling have been used with some success (for example Carrero-Pazos et al., 2018). It has been proposed that Radiance Scaling output should be used further in raster graphic editors such as Adobe Photoshop© with the "dodge and burn tool" and overexposure options (Carrero-Pazos et al., 2018) to better highlight images. Since the proposed Meshlab options work across the entire surface of the 3D model the stronger curvature of some complete panels or strong ridges present a stronger signal that in a sense "cloaks" the weaker signals of the local variations, i.e. the petroglyphs. It would be possible to make a selection to use these tools, but that would reintroduce the problem of bias in human decision making. Furthermore, the steps needed to increase visibility in this method do not directly process height values, but rely on pixel manipulation in image processing applications where some loss of control over the variables may be expected.

Another approach that has been proposed is the use of LIDAR visualisation technique in a method called "AsTrend" (Carrero-Pazos et al., 2016). This method delivers a compelling visualisation. However, it may be problematic since it uses yet another application LiDAR Visualisation Toolbox that was last updated in 2014 (https://sourceforge.net/projects/livt/) and uses unfamiliar file formats. It may in the future also prove problematic for rock art because it causes distortions on slopes (Hesse, 2010) which would especially effect carved lines. Carrero-Pazos et al. (2016) also propose the use of Adobe Photoshop's© toolset to enhance the outcome of their visualisation approach (Carrero-Pazos et al., 2018). This is problematic because the data is manipulated unevenly and without control. This reintroduces documenter bias, because the colour does not represent existing differences in depth anymore, and are more akin to tracings.

These approaches all have their uses, but could also be characterised as digital versions of manually traced rock art images. In the following, the authors describe a simple method to generate images with the compelling clarity of traced drawings or frottage images without further manipulation through raster graphic editors. The images generated in the final output are reduced to two-dimensions, but they preserve the objective, bias free advantages of 3D based documentation which provides a surplus of information for research, i.e. the correct spatial relation of petroglyphs and superimpositions. Lastly, the considerably reduced file size of digital frottage images makes them perfectly usable on every computer and in the creation of mobile apps for rock art museums and centres. The resultant images, similar in appearance to traditional rubbings, maintain their authenticity while significantly improving the visual contrast of the petroglyphs.

Before explaining our method, Reflectance Transformation Imaging (RTI) should be mentioned because it has already had a significant impact in the documentation of rock art (Díaz-Guardamino Uribe and Wheatley, 2013; Horn and Potter, 2018). This photogrammetric method alleviates the problem of large file sizes and produces excellent, high-resolution images. However, RTI cannot be used to create full 3D models, and is affected by directional lighting obscuring carved elements (as described above). For these reasons, we will not discuss RTI further here.

3.5. *Landscape approaches to 3D data processing*

Landscape analysis within heritage and archaeology has become increasingly reliant on complex three-dimensional datasets. The advent and wide scale capture of LiDAR data has facilitated this development, which has been utilised by a variety of disciplines from ecology, geography, and archaeology (Bewley and Rączkowski, 2002). The latter has enthusiastically embraced LiDAR as a revolutionary tool for site prospection and analysis (Bennett et al., 2012). The need to identify very specific topographic signatures has led to significant innovation within 3D Data processing and visualisation techniques (Bennett et al., 2011; Crutchley, 2010) that are now routinely housed within geographic information systems (GIS). On a landscape scale, archaeological features are typically present as micro-topography which is much subtler than the geographic background. Therefore, techniques that filter the natural from the anthropogenic are essential in landscape analysis. These issues are clearly similar to those outlined above, albeit on a significantly difference spatial scale. The need to highlight faint topographic features and remove macro-topographic structures, however, remains the same. The breadth of visualisation and analysis techniques for landscapes has been summarised elsewhere (Bennett et al., 2012) but some, most notably local relief modelling (LRM), have significant potential for the visualisation and analysis of petroglyphic imagery as it highlights micro-topographic features by removing macro-topography. The basic underlining principal is to defocus a topographic raster image (in ArcGIS using the focal statistics tool or in QGIS using the GRASS r.neighbours plugin) to a radius that is appropriate to the scale of the features you wish to highlight (Fig. 2a). Through this process small scale variation is removed by averaging cells to the surrounding pixel values. The values of the original raster are then subtracted (minus tool in the raster calculator for both ArcGIS and QGIS) from the defocused image revealing only the features smaller than the focal radius. This process is effective on both shallow subtle pictographs and deep incisions. Fig. 2 shows an example of the effects of this workflow. The size of features revealed relies on appropriate parameters, specifically the extent to which the topographic image is defocused (Fig. 2b–e). The typical workflow used in this paper involved the use of ArcGIS, using the focal statistics tool, initially with default values, before adjusting the cell radius in increasing increments until the image was defocused just beyond the point that the desired features

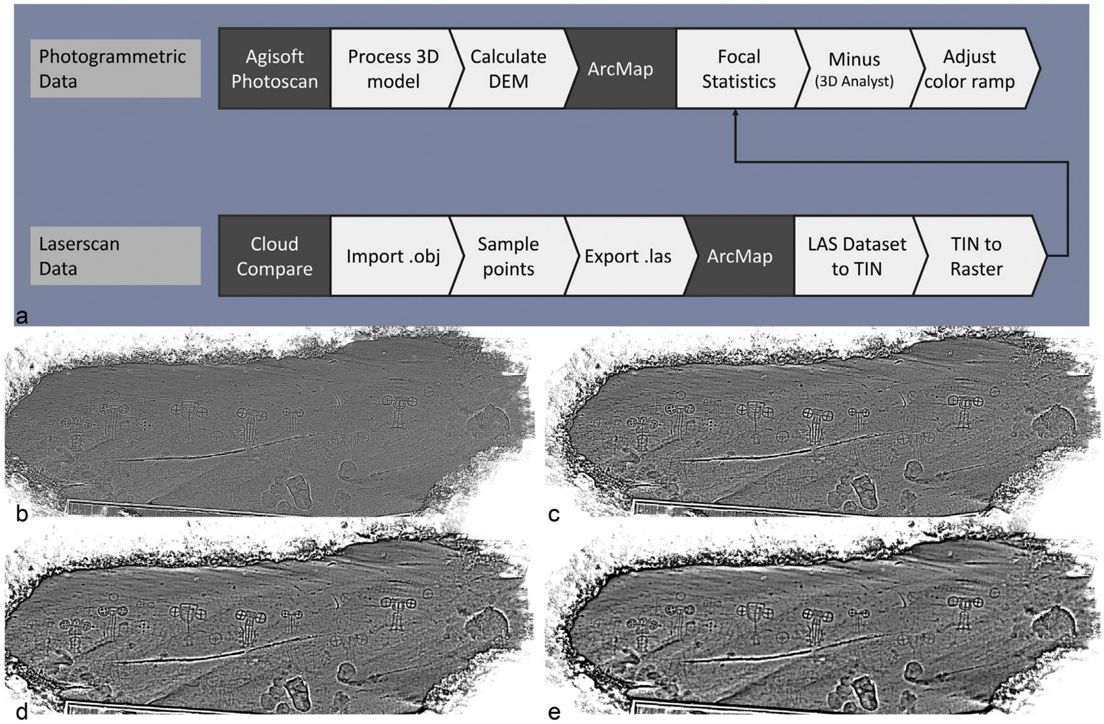

Fig. 2. Workflow of the data processing. The output in this example is produced in ArcMAP (a). Examples of different defocussing values (Focal Statistics tool): b.) 60 × 60, c.) 120 × 120, d.) 320 × 320, and e.) 640 × 640.

lose visibility. This allows the maximum highlight upon subtraction from the original raster data. In addition to the steps above, both ArcGIS and QGIS have dedicated, open source, local relief model plugins that can produce similar effects (the plugins take the workflow a step further, computing a 'true' LRM, however, these steps are more pertinent to landscape studies, Novák, 2014).

The output of the process requires an adjustment to the colour distribution to enhance the contrast of the image. This can be achieved by setting the standard deviation of the colour ramp to values ranging between 0.2 and 2.0 depending on the recorded surface. There is also a range of different colour gradients available. However, in this paper no improvement could be observed by choosing anything other than black and white gradients.

4. Evaluating visualisation techniques using the SHFA archive

4.1. The rock art panels

The dataset used within this paper results from fieldwork conducted in Tanum (Vitlycke (RAÄ 1:1), Finntorp (RAÄ 89:1, 95:1, 184:1), Hoghem (RAÄ 160:1), Bro (RAÄ 198:1), Fossum (RAÄ 255:1), and Gerum (RAÄ 311:1)), Gothenburg (RAÄ Askim 27:1), Scania (Frännarp (Gryt 1:1)) and the National Museum in Copenhagen (Engelstrup). The fieldwork was conducted in seasons between 2014 and 2018 (Horn, 2016; Horn et al., 2018; Horn and Potter, 2018). We will use the numbering system designated by the National Swedish Heritage Board (Riksantikvarieämbete).

All panels have a similar documentation history (Table 2) available through the SHFA. The earliest documentations, from the middle of the 19th century, were drawings and graphics of Gerum, Vitlycke, and Fossum. These are also the panels that have been documented the most. The first comprehensive documentation effort was made by Lauritz Baltzer during the 1880s recording almost all panels except Finntorp 95:1. Modern frottage exists for all sites conducted by Tanum's Hällristningsmuseum Underslös (THU), which record the known extents of each site. Only on panel Finntorp 95:1 were entirely new petroglyphs discovered during laser scanning by the Administrative Board of Västra Götaland (Henrik Zedig). Two additional anthropomorphic figures were discovered. These figures are only partially visible in our own recording as we avoided removing soil.

4.2. Advantages of GIS data processing of 3D rock art data

The following sections outline the key advantages observed when applying this technique to the SHFA dataset. Thus far, the process has produced results that heavily complimented the dataset and greatly facilitated interpretation and dissemination.

4.2.1. File size

For the storage and dissemination of the produced visualizations, the proposed method has a much reduced resource impact. The Tagged Image files (.tiff) produced through exporting the image from ArcMAP for full site models ranges between 12 and 32 MB. The exported images have a resolution of 600 DPI and a size of ca. 6900 × 5600 pixel. With the loss free compression of image formats such as .tiff or .png this can be improved further. Even for large sites like Gerum 311:1 or Bro 198:1 the.png files did not exceed 24 MB (Table 1). This results in more than a 90% reduction in file size, although, it must be kept in mind that these are no longer 3D models.

4.2.2. Visualisation of small details

This approach has the capacity to visualise very subtle details as small as the resolution of the 3D model permits. The panel Finntorp 89:1 is a large panel of ca. 6 × 5 m including at least 17 human figures (Horn and Potter, 2018). Two of these anthropomorphs are depicted engaged in intercourse. In the upper body of the female figure on the panel Finntorp 89:1, an outward swinging line could indicate female breasts. Directly below is a straight line angled upwards towards the back, while a similar second line is lower on the body and is a prolongation of the phallus (Fig. 3b, red arrows). Both lines could indicate a garment pulled aside for intercourse. The long hair seems slightly detached on the traditional rubbing (Fig. 3a). However, the new image

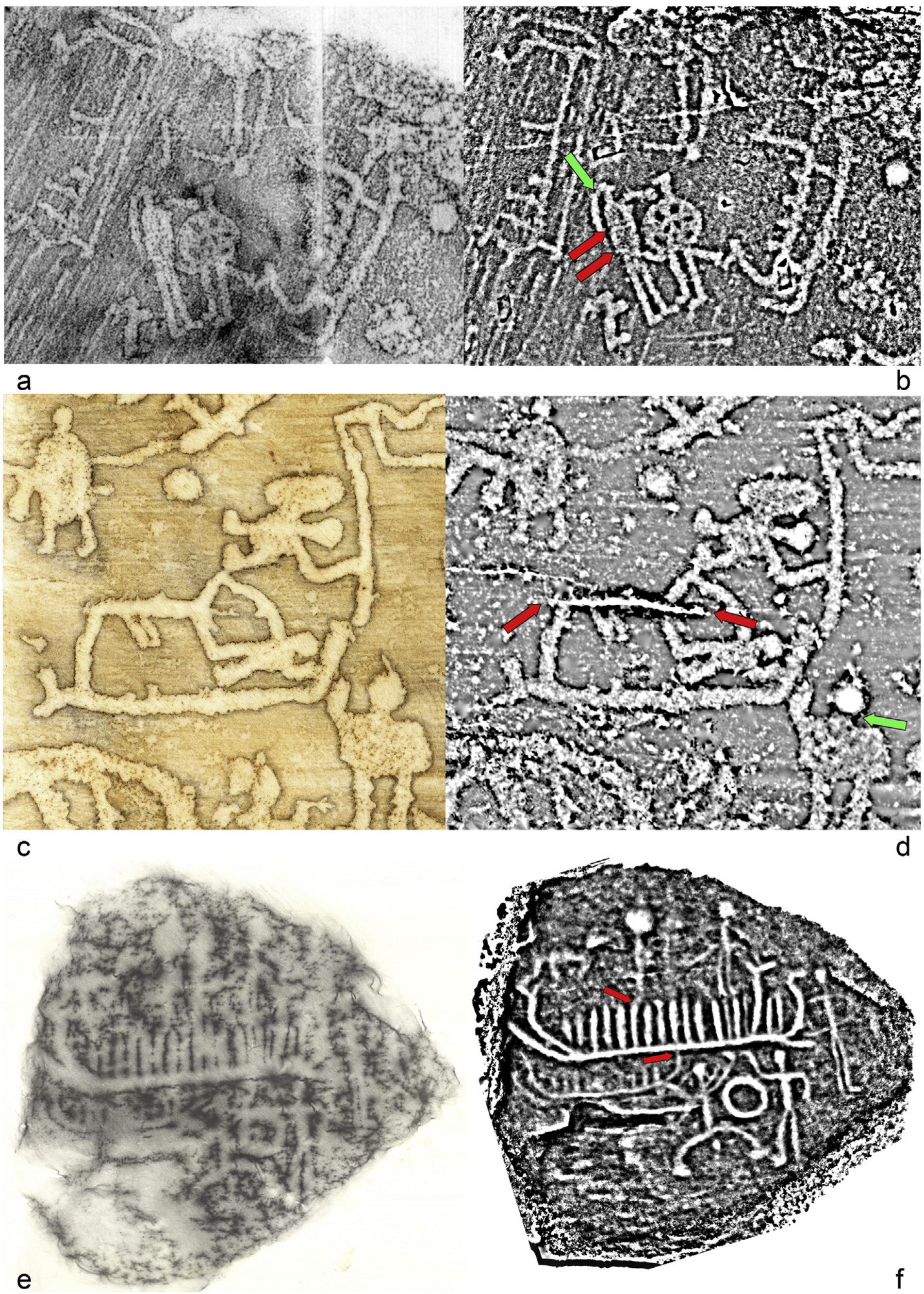

Fig. 3. Comparison between rubbings of images at various sites and the GIS processed output following the proposed methodology (if not mentioned differently based on Structure from Motion data): RAÄ Tanum 89:1 documented by the RockCare project using rubbing in 1999 (a) and the GIS processed output (b). Both figures ca. 20 cm. RAÄ Tanum 90:1 documented by Dietrich Evers using rubbing in 1970 (c) and the GIS processed output based on laser scan data (d). Human figures ca. 15 cm. Boulder from Engelstrup documented by Tanums Hällristningsmuseum Underslös using rubbing in 2014 (e) and the GIS processed output (f). The slab is 58 × 65 cm large.

shows that it is connected to the head by a thinner line which could represent a binding (Fig. 3b, green arrow).

On the neighbouring panel in Finntorp (90:1) there is a figure hunting with a spear. The spearhead is ca. 7 cm long, but shows surprising detail in the digital LRM (Fig. 4). The edges follow from the point of the concave trajectory before sharply curving back towards the socket (Fig. 4, red arrows). Without going into detail, spears with such sharply breaking edges are known from the Early Nordic Bronze Age and belong to the types Bagterp and Hulterstad (see also Bertilsson, 2015; Horn and Potter, 2018; Jacob-Friesen, 1967).

4.2.3. Equal colour distribution

When compared to traditional rubbing, digital data files possess an equal distribution of colour whose variation depends only on the structure of the recorded surface. In Finntorp 89:1, for example, the conventional rubbing has a lot of graphite surrounding the male figure because it is a very shallow carving and the documenter wanted to make sure every detail was captured (Fig. 3a). However, these efforts obscured the nose-like shape on the figures head as well as the outline of the shield. The processed digital image shows the nose and full extent of the shield on the male figure in Finntorp 89:1 (Fig. 3b).

A highly detailed rubbing of human figures and a ship on the panel Finntorp 90:1 was prepared in the 1970s by Dietrich Evers (1991). There is an animal on the panel that could be a bull or another animal. The rubbing fails to indicate that the line which seemingly forms the body of the animal is in fact a natural crack in the rock surface (Fig. 3c). The processed LRMs indicate that this is not an engraved line, but instead damage that obscures the original engraving (Fig. 3d, red arrows). Presumably, Evers did not apply graphite vigorously enough in that part to visualise the difference, perhaps because he believed that an engraved figure had to be there.

Rubbing paper is difficult to fix onto small boulders like the one

Fig. 4. GIS processed output from laser scan data of a hunting scene on RAÄ Tanum 90:1. The human is ca. 20 cm large. In situ 1904 with painted figures (a), rubbing by Tanums Hällristningsmuseum Underslös (b), and the GIS processed output (c).

from Engelstrup, Denmark. As a result, the graphite is distributed very unevenly and weakly in some places. Even the strongly carved central ship is not visible on the engraving in full detail because the rubbing left less pigment towards the border of the carved surface (Fig. 3e). Conversely, every figure is clearly visible in the digital LRM, with many details and other information addressed below (Fig. 3f).

Since the colour in the LRM only depends on the carved features and not the documenter, it is possible to estimate depth differences between engraved features. Depending on the colour ramp chosen, the lighter or darker a feature is, the greater its depth. It is possible to recognize immediately that the figure holding the boat in the scene on panel Finntorp 90:1 has a cupmark as head (Fig. 3d, green arrow). In Finntorp 89:1, the mid-section of both partners is engraved shallower than the head and the feet (Fig. 3b). On the boulder from Engelstrup it is possible to observe that the large ship and the ring are the features which are most deeply engraved (Fig. 3f).

4.2.4. Superimposition

The possibility of judging depth differences based on colour in the visualisation allows us to investigate a particularly important feature for the relative engraving sequence: superimpositions. This can be demonstrated on the boat with the spearmen on the panel Finntorp 184:1 (Fig. 5a–c). The upper body of both figures cuts into the upper line of the boat (Fig. 5a, red arrows). This line ends in a stem that curves upward from what seems to be an older line that runs longer (Fig. 5a, green arrows). At the aft end the line overlays a stem or prow that curves upwards, but ends shortly afterwards (Fig. 5a, violet arrow). Underneath, the older line reappears slightly askew and is also superimposed by the keel line of the larger boat at its terminus (Fig. 5a, violet arrow). This keel line reaches in an oval curve from the stern where its terminus curves outward. Here the keel line superimposes the older line. At the aft end, a younger line forms another stem, and is also curved outward at its terminus superimposing the keel line (Fig. 5a, orange arrow). Another superimposition can be observed on the left warrior of the spear fighting scene on panel Finntorp 95:1 (Fig. 5d–e). The warrior's knees seem to extend in front of the shin. The lower legs cut across, but are a weaker engraving, i.e. they show more of the irregularities of the original rock surface (Fig. 5d, red arrows). This means that a second pair of legs was possibly added to the original pair of legs. This is a feature that has also been observed on panel 89:1 in Finntorp (Horn and Potter, 2018). Other superimpositions can be observed on the couple in Finntorp 89:1. The line of the sword's sheath cuts into the lower outer line of the shield, but is itself intersected by the left leg. There is no great difference between these lines. Here, digital frottage provides information on the production sequence, and not about transformative events (Fig. 3b).

Other examples of the visibility of superimpositions come from the famous couple on the Vitlycke panel (Tanum 1:1) (Fig. 6a-b). The mouth of the warrior overlays the figure with long hair (Fig. 6a, red arrow). The phallus also superimposes that figure, and in fact, only stops at the petroglyph's back (Fig. 6a, green arrow). The sword's sheath cuts into the hind leg of the warrior (Fig. 6a, violet arrow). The line that seems to connect both figures at the knee has been interpreted as a binding, symbolizing some kind of union (Fredell and Quintela, 2010). Both the legs of the warrior and the front leg of the long-haired figure cut across this line. Only the hind knee of the warrior is directly connected. From there the line angles downward and is situated below the other knees (Fig. 6a, orange arrows). There are two simpler explanations for the line. It could have been an older line that was not recognized and the couple were accidentally placed over it. Alternatively, it could be a reference line to help achieving the proper distance between both figures as their closeness would make placing them a difficult task.

Vitlycke 1:1, is a scene with a warrior seemingly having sexual intercourse with an animal (Fig. 6c-d). In the rubbing it appears as if the animal has four legs, and penetration is indicated by a short line approximately at the anthropomorphic warrior's centre. In the digital frottage, the complexity of the scene becomes visible in greater detail

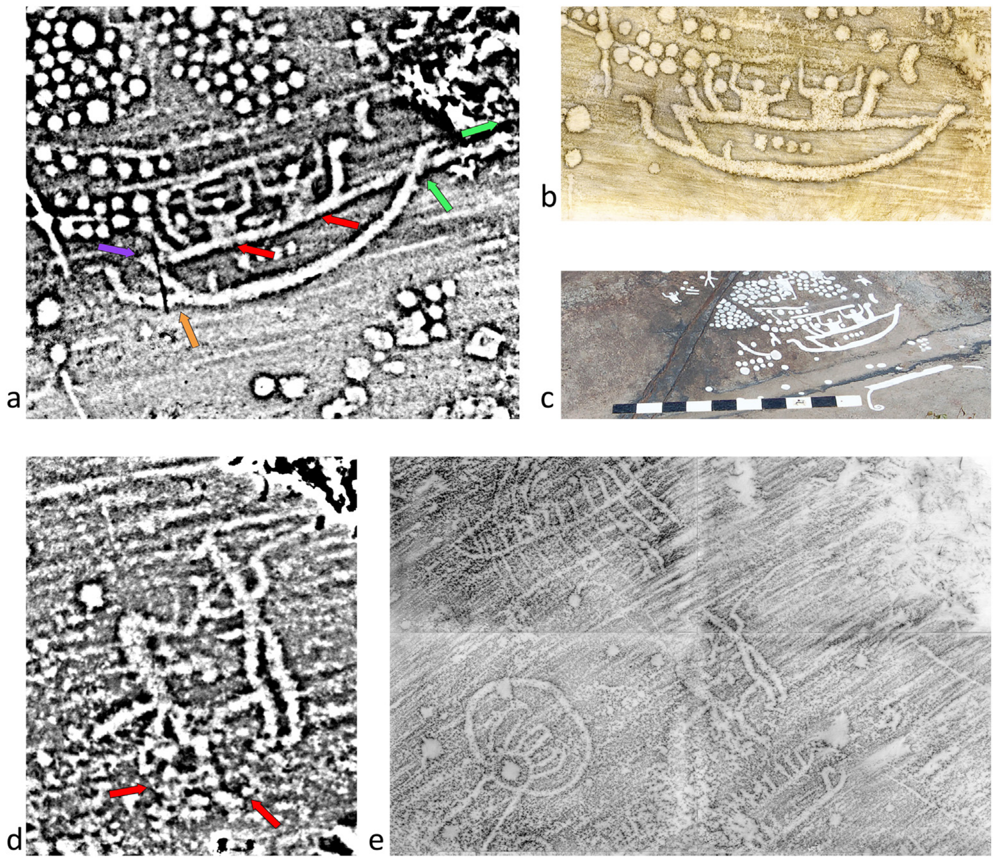

Fig. 5. Examples of superimpositions in rock art (if not indicated differently based on Structure from Motion data): a.) scene with boat and crew on RAÄ Tanum 184:1 with comparative images from a rubbing by Dietrich Evers (b) and an in-situ photo by the Tanums Hällristningsmuseum Underslös with the figures chalked in (c). The boat is ca. 40 cm wide. d.) two fighters on RAÄ Tanum 95:1 with a comparative rubbing by Tanums Hällristningsmuseum Underslös. The taller figure is ca. 25 cm large.

(Fig. 6d). The presumed animal leg is in fact a half circle superimposing the human figure and continuing shortly above the animal's tail (Fig. 6d, red arrows). This potentially indicates the phallus of the warrior, although there are several other possibilities. The tail may cut the half circle (Fig. 6d, green arrow). Therefore, the animal was potentially applied to the scene last, indicating that this scene was not always a warrior-animal-intercourse scene. The overly-long limb is slightly misaligned with the body-leg-line of the warrior and somewhat thicker showing another superimposition (Fig. 6d, violet arrow).

On the rubbing of the stone from Engelstrup, the larger ship merely seems to be placed above the smaller (Fig. 3e). In the digital frottage, one of the stems of the smaller boat is clearly cut by the keel line of the larger boat (Fig. 3f, red arrows). Additionally, other details become clearer, for example the feet of the central figure above the boat are superimposed by the crew-strokes (Fig. 3f, red arrows).

In all the presented cases, GIS data processing can visualise multiple superimpositions. This would require many differently angled and lit snapshots if the 3D model would have been used directly. One point, however, remains problematic. When the engraved feature is very deep then there is no indication of structure in the image, for example, cup marks are usually very deep and they only show up in white, meaning that any internal structure is lost, and with that potential further information about the sequence of superimposition.

4.2.5. New discoveries

In a sense, observing superimpositions and very fine details are all new discoveries. However, by themselves they do not necessarily change our view of an image or a scene fundamentally. The base for the following case is of course the 3D model itself. Describing the scene here only serves to highlight the amount of information processed raster datasets can convey in a single image. The following also demonstrates that new discoveries are even possible on panels that have been documented for over 150 years.

One such example is the Gerum panel which was first documented by Axel Emanuel Holmberg in 1848 (Fig. 7a). The panel in Gerum is a large site with a currently known extent of 9 × 6 m. The last published overview over the region puts the number and identification of petroglyphs as follows (Bengtsson and Olsson, 2000): 82 boats, 36 anthropomorphic figures, 23 animals, 14 foot soles, 3 ring crosses, 2 circles, 1 cross, 1 mast-like figure, 3 obscure figures, 119 cup-marks, and several lines (Fig. 7b). The site was re-documented in July 2018 using multi-image photogrammetry. The subsequent analysis is based on observations in the field, the 3D model (Fig. 7c), and to a greater degree on the GIS processed DEM, since the latter was able to visualise most figures without the necessity of shifting the lighting angle continuously (Fig. 7a) (Horn and Potter, accepted).

During this investigation more figures than previously published were discovered even though some parts of the upper panel, which also bears motifs, could not be documented since long, heavy sandbags had been put in place to guide water flows around the panel. The increase in figures compared to the last published documentation is in brackets (Bengtsson and Olsson, 2000). According to this count, there are 95 boats (+13), 43 anthropomorphic figures (+7), 28 animals (+5), 16 foot- or shoe-soles (+2), and 187 cup-marks (+68). In addition, there are 13 potential boats, one potential animal, and one potential foot- or shoe-sole (Fig. 8). The cup-mark count includes cup-marks that have been used as heads of anthropomorphic figures (Horn, 2016) which may explain some of the discrepancy. Another explanation for the difference is that the latest publication did not record the lowest section of the panel (Bengtsson and Olsson, 2000), but older documentations did not identify all of the motifs, i.e. Axel Emanuel Holmberg (in 1848) and Lauritz Baltzer (in 1886). Some of the motifs may be so faint that they escape visual and tactile detection, and could only be made visible with the sensitive and visually enhancing digital methods used here (Horn et al., 2018; Horn and Potter, accepted).

New discoveries have also been made on a smaller scale. One scene

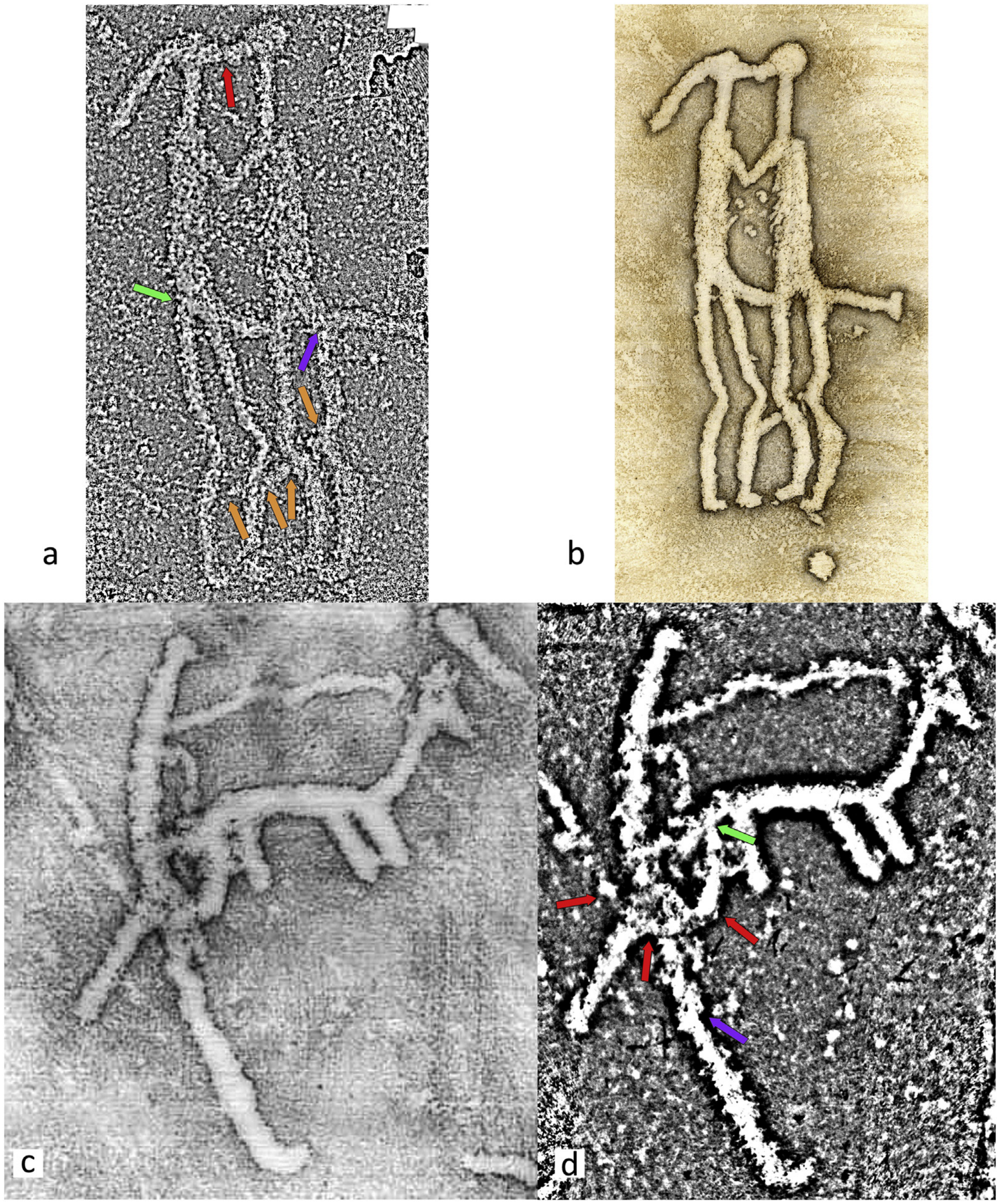

Fig. 6. Examples of superimpositions in rock art (if not indicated differently GIS processed 3D data): a.) intercourse scene on RAÄ Tanum 1:1 with a comparative image from a rubbing by Dietrich Evers (b). c.) zoophilia scene on RAÄ Tanum 1:1 (rubbing by the RockCare project) and the GIS processed output (d).

on the Vitlycke panel shows two warriors engaged in a spear fight. Currently the scene is painted in red for the presumed benefit of visitors (Fig. 9a). The paint presents both warriors with a sword sheath and a phallus. The larger warrior possesses exaggerated calves, two horns, and a phallus. On the upper body, a cupmark is placed right next to the body under the armpit. The processed image shows that the cup mark is not beside the upper body, but that both intersect (Fig. 9b, red arrow). Furthermore, around the horns there are 3–4 more lines engraved which are not indicated by the current paint (Fig. 9b, green arrows). In fact, an older painted version of the figure shows the head much more precisely with this "hairstyle" (Horn, 2018).

The smaller warrior has both arms on the spear and carries a sword sheath without any indication of a chape. In the painted version, the figure seems to possess a phallus and exaggerated calves comparable to warrior 1. However, no horns are indicated, and the phallus is larger. Phallic warriors are common in Scandinavian rock art, so it was a great surprise that the 3D model and the processed raster image showed the engraved feature as what may instead be an animal intersecting the warrior. The back of the animal is placed at belt height so that the head, neck, and front part of the body replace the phallus, with the tail forming the sword sheath. The first front leg substitutes the testicles, the next two legs are part of the front leg of the warrior, and the last hind leg is perhaps indicated in the back leg of the warrior. The placement is so precise that we may rule out accidental placement (Fig. 9b, violet arrows).

This is not simply another phallic warrior, but a case of the transformation of Scandinavian rock art motifs; a topic which has recently received more attention in research and has been interpreted in a number of ways (Bertilsson, 2015; Horn et al., 2018; Horn and Potter, 2018; Ling and Bertilsson, 2017). The main point here is that the output generated by the LRM processed 3D data comprises the complexity of the scene into one readable image. Conveying a similar amount of information would require several screenshots from the 3D model itself.

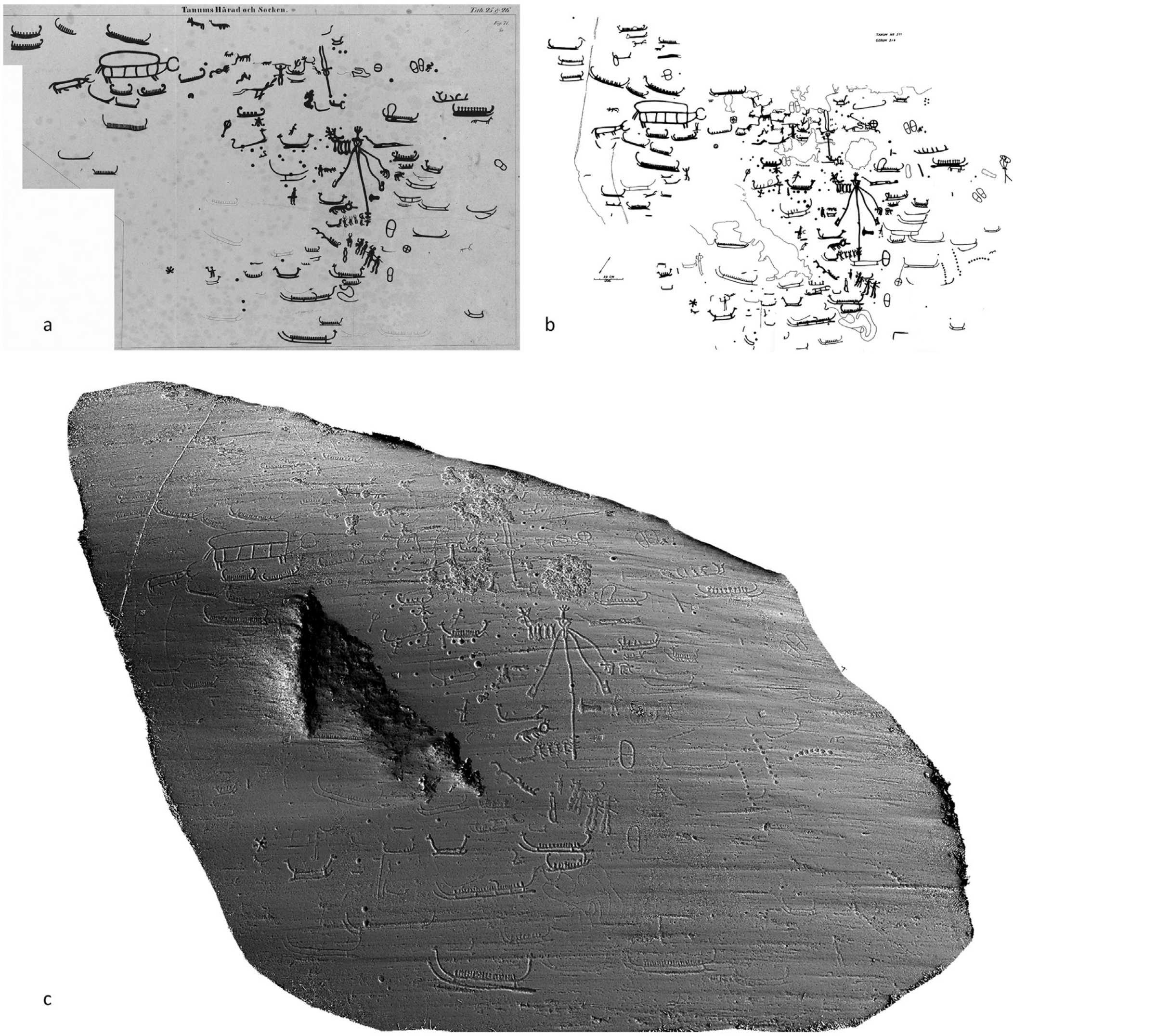

Fig. 7. Documentations of the panel in Gerum (RAÄ Tanum 311:1). The panel is 900 × 600 cm large: a.) Indian ink drawing by Axel Holmerg, 1848; b.) tracing by Tanums Hällristnings Museum, Underslös, no date; c.) Snapshot of the 3D model (Structure from Motion) taken in Meshlab, 2019.

5. Conclusion

This paper has highlighted some of the problematic aspects of three-dimensional and older documentation techniques for rock art, i.e. colour distribution, visualising depth, file size including storage and processability, and the dependency on multiple interchanging lighting angles. It has been proposed that GIS processing of DEMs from 3D models can remedy some of the problematic issues. The GIS processed output produces high quality images with small file sizes that are capable of visualising large panels and small details including depth differences in an equal colour distribution. This provides an excellent visualisation of the chronological and spatial relationships of motifs making complex panels understandable in a single image. However, investigations should not depend on such images alone, but should instead combine observations in the field, 3D models, older documentation, and the GIS processed DEM images to approach rock art as holistically as possible. This complimentary approach to rock art documentation can facilitate both the wide-ranging dissemination of results and a greater clarity of interpretation.

The article argued that beyond being a good tool for visualisation, the proposed method also provides a potent approach to researching petroglyphs. Some of the superimpositions imply a longer chronology in which the images and scenes in Scandinavian rock art were transformed. Therefore, there must have been a temporality to their meaning. The changing face of the panels may imply a change in the narrative structure and the stories and myths linked to the images. This opens new opportunities for research into the relative chronology and the changing social meaning of rock art that future projects will have to address.

The dataset presented here demonstrates just a sample of potential applications. While the method was developed using Scandinavian petroglyphs it does not depend on this data. It could be applied to other 3D models with small depth difference on larger surfaces. This could be petroglyph panels from other sites, carved menhirs, incised script, coins, reliefs, plaques, decoration on metalwork, etc. This means there is no reason the method cannot be used with Late Bronze Age stelea in Spain, Viking Age rune and picture stones, situlae dating to the Early Iron Age, sigilata stamps from antiquity, etc. The applicability of the method to each of these materials would of course require testing. Since the method is free and does not have any high knowledge barriers, these tests can be conducted quickly if the 3D data has already been acquired. For petroglyphs or any other material, increasing volumes of three-dimensional data and the widening adoption of photogrammetric and laser scanning based techniques will only serve to increase the importance of innovative, comparative data processing techniques.

Fig. 8. Gerum (RAÄ Tanum 311:1): a.) Output of the GIS process; b.) Drawn interpretation of a. prepared through tracing in Adobe Photoshop©.

Declaration of competing interest

None.

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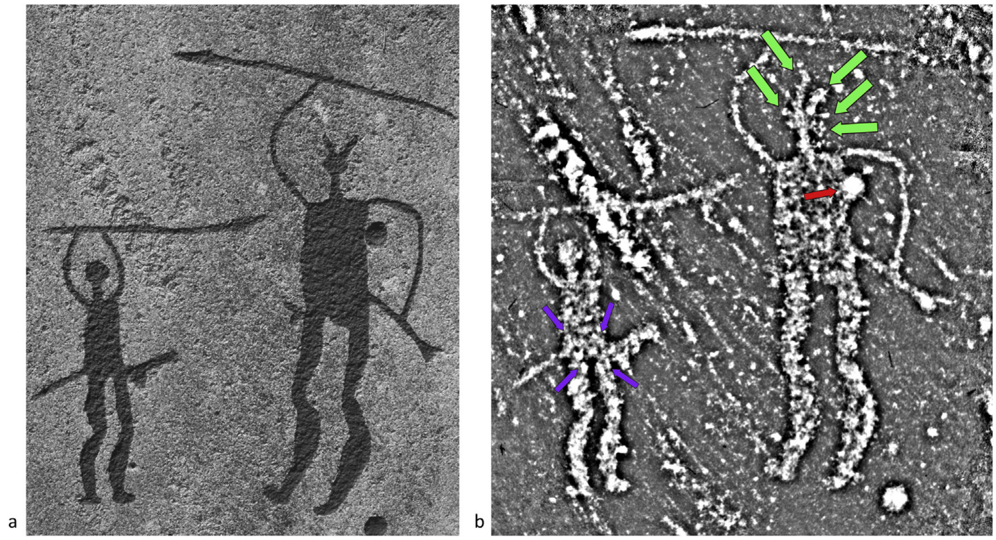

Fig. 9. a.) Photo of the current, painted state of the spear-fighting scene on RAÄ Tanum 1:1 and the GIS processed output (b). The larger figure is ca. 30 cm large.

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