RESEARCH

An evaluation of Substance Painter and Mari as visualisation methods using the Piraeus Lion and its runic inscriptions as a case study

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Abstract

This paper explores the effectiveness in the use of texture painting software packages, which are more commonly used in the film and game industries, as a method for detecting and recording carvings on non-planar surfaces. This new approach is demonstrated through a case study of the Piraeus Lion, a sculpture in Venice which has documented engravings that are subtle and have proven difficult to fully recorded and interpret using traditional approaches. Through the creation of a new digital documentation of the Piraeus Lion using Structure from Motion, the model was processed using existing methods and other experimental visualisation techniques. The outputs from these were then compared to the those from two software, Substance Painter and Mari. These software packages helped to visualise the carvings and showed that the method has potential for a wide range of uses, both within epigraphy and other fields of study relating to carvings on stone including rock art and runology. The presented method is intended to be used alongside existing digital and analogue methods as a tool for annotating, evaluating, and discovering new carvings in their original context. In particular, Substance Painter offers a repeatable, easy to use, and intuitive solution to creating easily distributable visualisations and annotated models.

Keywords Carvings, Substance Painter, Rock art, Statue, 3D, SfM, Visualisation, Venice, Greece

Introduction

This paper presents the results of a new digital documentation of the Piraeus Lion, a fourth century BC marble statue presently located in Venice, Italy. The first documented location of the sculpture was in the port of Piraeus, Greece, where it formed a well-known landmark until it was taken as war booty in 1688 by the Venetian navy.[1] The sculpture, which is on display outside the entrance to the Arsenal complex, stands at around three metres tall and is sculptured in what may be Hymettian marble [1]. The sides of the statue are covered in Runic inscriptions of the eleventh century AD, probably made by Swedish mercenaries in Byzantine employ.

As well as implementing and testing two new methods of visualisation, this investigation aimed to examine and compare digital capture and imaging techniques previously utilised in rock art and epigraphy studies (introduced below) to see if they could be adapted and applied to this medium.

When assessing rock art, subjects are typically inscribed on relatively flat surfaces, which makes it possible to utilise a variety of methods to enhance the visibility of smaller details on the panels (see below). In the case of the Piraeus Lion, the sculpture has more than one side and an undulating non-planar surface, meaning that an alternative method was required to visualise the details of

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[1] The Sculpture is very likely to be a funerary monument, in which case the Piraeus location is not the original setting of the lion.

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the inscriptions in their original context. This was desirable as it would not only aid the understanding of the full carvings and their placement on the statue, but also how they relate to each other. It is advantageous to be able to see the carvings as a whole prior to trimming to individual sections so that potential new carvings can be identified in areas that are not ordinarily examined. While additional delimited assessments of carved areas will also be included in the eventual interpretation of the carvings, this paper presents a method for visualising and evaluating the entire 3D surface with the carvings in their holistic context. By using the digital texture painting software *Substance Painter* and *Mari*—both of which are more commonly associated with the creation of 3D models for video games and film—we were able to make the smaller carved details on the statue visible in a more interactive[2] way than through traditional, non-digital techniques (for example, frottage or tracing). These approaches essentially allow complex, three-dimensional surfaces to be 'unwrapped' in order to extract key micro-topographical details which are then visualised using a variety of filters, and can even be non-destructively annotated. There are several existing methods for visualising fully three-dimensional models which will be introduced and compared here: they will be assessed in terms of results, ease of use, time taken to process, their potential to work with high-polygon models, practicality, and their possibility of creating lasting texture maps. Other software which can be used to enhance features, such as Adobe *Photoshop,* have limited 3D tools and will not be introduced here. In the case of *Photoshop*, the 3D elements it previously had have been superseded by those in *Substance Painter*, which is now also owned by Adobe. While other 3D software can be used to similar effect, there are often steep learning curves and prohibitive price tags that prevent their widespread use.

There are a number of methods for visualising stone carvings on 3D models, ranging from complex programmatic solutions [2–5] to simpler solutions using tools readily available to archaeologists [6–8]. However, a large portion of these methods can only be applied on essentially flat surfaces [2, 3, 9, 10], the plane of an object surface [11] or—in the case of Sapirstein [5], objects that can easily be flattened programmatically. Several methods, for example, morphological residual modelling (MRM)—a method in which a high-resolution model is compared against a smoothed low-resolution model—can be applied to 3D surfaces, but require trial and error to get a good result [12–16].

There are also other similar methods including *Xshade* [6, 17], and APSS [17, 18], as well as using simple tools like radiance scaling within *MeshLab* [6, 17, 19–22]. Another method that has recently been presented used ambient occlusion to find the areas where light would not fall from every angle [4].

Reflectance transformation imaging (RTI) could certainly be a useful tool here [23–27], particularly using vRTI from planes of the 3D mesh [28], but we were interested in finding a way to work with a visualisation of the entire mesh in 3D as we wanted to see the relative positioning of the carvings.

While complex solutions such as Sapirstein's [5] and Rolland's [4] are not undesirable, they often lack user-oriented interfaces and/or practical instructions adopted to non-programmers. The challenges addressed in this study relate to developing a workflow that suits models of non-planar surfaces on full 3D models, yet which can still be executed by non-specialists, with repeatable and shareable results.

The majority of these examples, excluding RTI and those that reduce the 3D form to 2D forms (e.g. LRM), retain the properties of the 3D model, i.e. scale, carving depth, etc. This is also true for the method presented here as it works from the original carvings. The exception to this is when it is used with a decimated low-resolution model as this relies on baked information (as will be discussed below).

It should be noted from the outset that this paper does not intend to dismiss other more traditional or existing digital methods. The strongest analysis of any surface is achieved by utilising the results of as many suitable methods as possible in tandem to create a complete assessment [29]. The aim of this paper is to add to the existing toolset by determining whether 3D asset texturing software is a viable method for highlighting carvings. The main focus of this paper is on the visualisation of carvings, with the purpose of seeing them in their original context, and in the discovery of new carvings. As this paper presents new methods, it is not advantageous to rank specific existing methods as it is impossible to be unbiased about one's own methodologies. Additionally, interpretation in these methods is highly subjective and the results can differ greatly depending on the medium it is applied to. As such, they are presented as alternative and additional methods that can also be used to help visualise carvings. This method does not represent the end point of an investigation into carvings on a surface, but more of a starting point in which carvings can be identified and annotated on the surface. While it is still

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[2] Interactive in the sense that it is possible to zoom in, rotate, relight from different directions, and annotate non-destructively. This interactivity offers a greater sense of authenticity for researchers working with the model, and enables easier access, analysis, and make it easier to present ideas through annotation.

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possible to measure carvings and depth on the 3D mesh, that is not the main intention of this method.

History of the sculpture and the attempts at reading its inscriptions

The history of the statue is well-documented [1] as being an ancient funerary-type monument (later reused as a fountainhead), sculptured and put up somewhere in the vicinity of the Athenian port of Piraeus, Greece, probably in the 360 s BC. At some point in the Classical period the lion was moved to central Piraeus and became such an important landmark at the harbour that Piraeus became known in the Middle Ages as *Porto Drako* ("Port Beast" in Greek) or *Porto Leone* ("Port Lion" in Italian). The statue was taken to Venice in March 1688 as a trophy after the 1687 Venetian victory over the Ottoman Turks at Piraeus and Athens, and was put up in its present location of display after some repairs in 1692. An 1890s plaster cast of the lion is exhibited in the National Museum of History in Stockholm, and a full-size marble copy was erected in the port of Piraeus in 2002.

In the final years of the eighteenth century, the Swedish diplomat and linguist Johan David Åkerblad noted that the lion was covered in three runic inscriptions, and the statue and its carvings have since been much debated by Scandinavian runologists [30–32]. The decorative nature of the carvings, including the spiral design and snakes head motif, display many similar characteristics to runestones found in the region of Uppland, Sweden. It is most probable that the inscriptions were made by Swedish mercenaries—so-called Varangians—in the employ of the Byzantine emperor in the eleventh century AD [1].

The main difficulties in interpreting the runic inscription have been the eroded state of the surfaces as well as the near-translucency of the marble. In spite of numerous reading suggestions [30, 33, 34] there is no consensus of the contents of the inscriptions. The most recent attempt by Snædal [1] combining older readings with her own substantial examinations, highlighted the damaged state of the inscriptions, with many eroded sections and musket holes from the 1687 fighting. Snædal's reconstruction of the texts show that the first and the third runic carvings were made by groups of Swedes commemorating fallen comrades, and that the smaller second carving was just a short graffito.

Recording the lion

The statue was recorded by creating a 3D model using Structure from Motion (SfM). SfM, a form of digital multi-stereo image photogrammetry, has been used extensively in archaeology and follows well established workflows [28]. The method as employed in this study used a structured set of photographs taken by the authors, extensively covering the surface of the statue. These were processed using *Agisoft Metashape*[3] to produce a 3D mesh.

In total, 1988 photographs were taken of the sculpture, collected first along vertical axes and then in concentric circles to ensure adequate coverage of all surfaces. Additional photographs of the top of the sculpture were taken on a ladder and with a monopod. The camera was a mirrorless Canon EOS R5 with a Canon RF 28–70 mm *f*/2L USM lens locked to 28 mm. This particular focal length (the shortest) was chosen to avoid accidental adjustment during recording which could impact the results.

The photographs were processed in *Agisoft Metashape*, using a standard workflow for full 3D models [6, 17, 26, 35, 36]. All backgrounds in the photographs were manually masked to achieve shorter processing times and a cleaner result. The dense point cloud confidence was calculated and all values below four (i.e. low quality points) were removed (Fig. 1).

The lion model was created in three separate iterations, a high-resolution model (88 million polygons), a medium-resolution model (22 million polygons) and a low-resolution model (200,000 polygons).[4]

Due to the difficulty of creating UV maps (2D coordinate representations of the 3D geometry which allow for textures to be applied in the correct position on a mesh) for high-resolution models, the workflow needed to allow for UV maps to be created directly within *Agisoft Metashape*. As such, textures were created within the software, automatically producing UV maps for all models. All of the meshes were then exported from *Agisoft Metashape* as.obj files.

Testing in Substance Painter and Mari

Mari and *Substance Painter* are two standalone software packages with similar functionality that allows users to create textures for 3D models. Both software utilise the geometry of input 3D meshes to determine the placement of textures that can relate to rust, dirt, grime, etc. in a realistic fashion based directly on the characteristics of the mesh. These characteristics are determined by calculating texture maps (as described below), traditionally using a higher-resolution (more detailed) mesh to "bake"

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[3] https://www.agisoft.com/ (accessed 12.07.2023) While it is acknowledged that other photogrammetric solutions exist, this is the software that the authors are most experienced with.

[4] The average edge length was also calculated for each of the models where larger values indicate lower resolution. High: 0.004237, Medium: 0.007814, Low: 0.058071.

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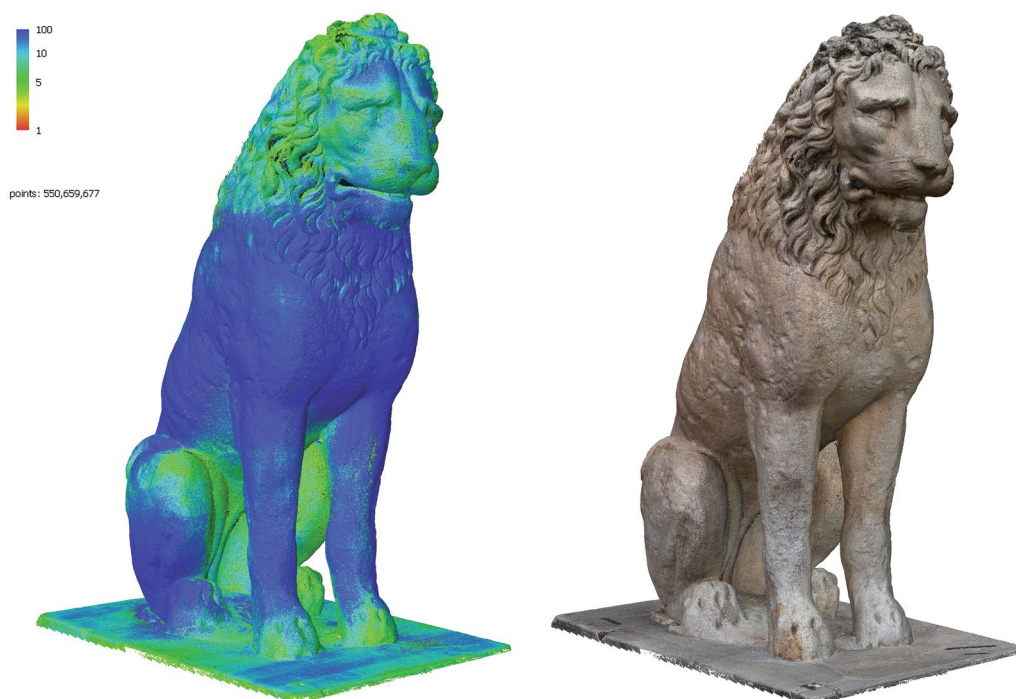
Fig. 1 The cleaned dense point cloud in Agisoft Metashape, with the scaled point cloud confidence on the left

details into the texture maps that are not present on a lower-resolution version of the same mesh. This reduces final polygon counts and makes the mesh more hardware efficient for animation and games. Both software can make use of the curvature of a mesh to dynamically place colour, i.e. where the model has either convex or concave features, which made it possible to utilise this software for visualising carvings on 3D surfaces.

The high-resolution model was tested in both *Substance Painter* and *Mari* as the base for the curvature map to observe whether there was a noticeable difference between that and the medium-resolution mesh (2 GB). However, it was determined that although possible, the size of the high-resolution mesh (5 GB) was too large to run sufficiently smoothly for any analysis to take place in *Substance Painter*, and the difference in detail level between the two resolutions was determined to be negligible. Additional tests were made in *Substance Painter* using the medium-resolution model, and the

low-resolution model with the high-resolution model baked down to it.

The low-resolution workflow involved bringing the UV-mapped[5] low-resolution polygon model of the sculpture into *Substance Painter* and baking (read: rendering) the normals (Fig. 2),[6] height, curvature, and ambient occlusion from the detail of the high-resolution model down to 2D maps, which would then be projected onto the lower-resolution model. These maps were then used to drive filters within *Substance Painter* (See Fig. 2 for overview of method). While this still makes use of the high-resolution model, it is only used for a short period of time while the maps are baked. Following this, the light-weight low-resolution model is used (∼ 20 MB), with the detail of the high-resolution model projected onto it, meaning that it can be used on less powerful computers. While this transition from 3 to 2D removes 3D data including depth [37], the baked maps retain enough surface detail to create an accurate visualisation of the small details, while also reducing file size and demand on hardware (Fig. 3). When only using a higher resolution mesh, the maps are baked from the mesh to itself.

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[5] UV mapping, or unwrapping, is the practice of separating a 3D surface into segments which can be represented in a 2D space. The 2D space is cartesian in nature and named after its axes U and V, which replace the usual X and Y to differentiate between 2 and 3D space. When a texture map is created in Agisoft Metashape, it automatically unwraps the model creating a UV map. The texture is then placed on the 2D surface and is matched by the UV coordinates into its correct position on the 3D mesh. This means that any additional marks or annotations that are added to the 2D texture file are added to the appropriate position on the mesh.

[6] A 2D representation of the direction of each polygon which can be used to add higher perceived detail to a model without increasing the polygon count. This image, or map rather, can be used by the software to calculate where colour should be applied to surfaces based on direction, small details, convex/concave areas, etc.
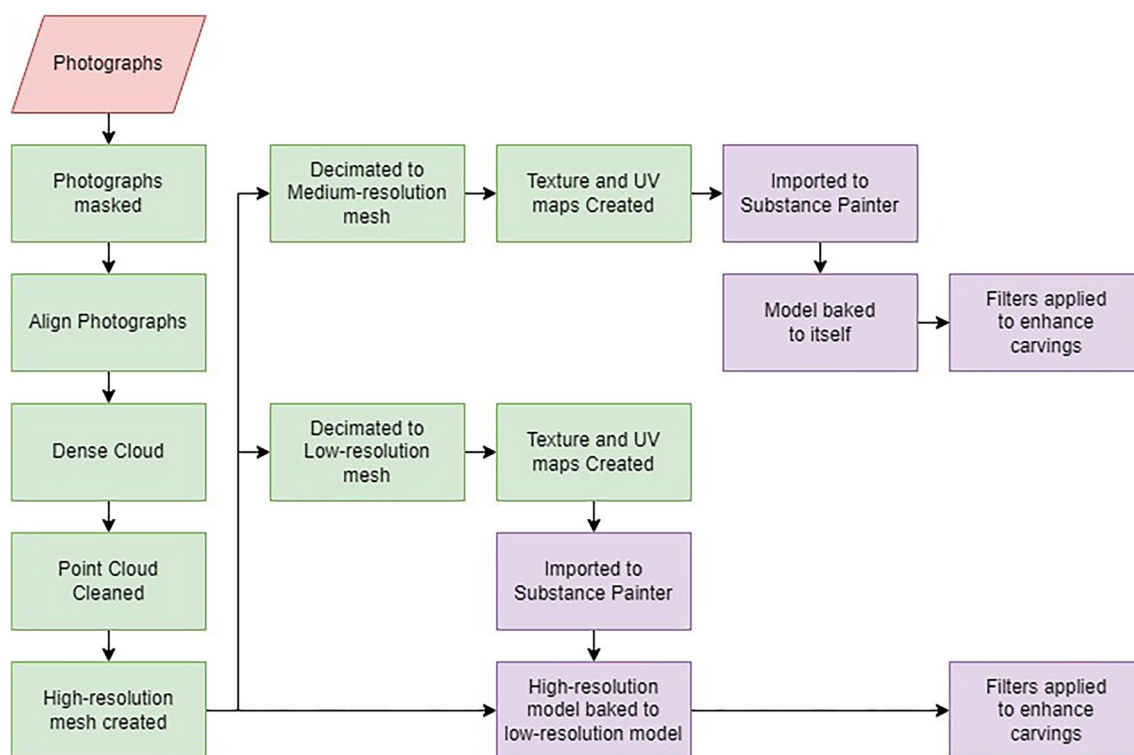
Fig. 2 Flowchart showing the process of the two baking methods in Substance Painter

The curvature map was primarily used for the methods described here. This map determines where curvature deviations, i.e. convex and concave features, are present on the model surface, based on the normal map. A detailed description of the methodology and the results are given after a comparison of methods.

Comparison of methods

In order to determine the usefulness of the proposed methods, they must be compared to other existing and known visualisation techniques. In the interest of openness and the democratization of methodologies, a brief overview of how the processes were carried out—from start to finish—will be given below. There are two areas of the lion which have been focused on by research, represented by two different sets of carvings on either side of the lion. Both of these areas will be presented below for each method.

The results of these tests are to be used as a baseline for which the viability of *Substance Painter* and *Mari* as visualisation tools can be assessed. For each method the same computer hardware was used (Intel 13900 k, Nvidia RTX 4080) to evaluate how long each method took. Where possible, the high-resolution model was used, but the medium-resolution model was chosen when it was more sensible due to lengthy processing/testing times or

difficulty working with the model. Many of the methods described below are similar techniques utilized in different ways, and primarily work with a high-resolution model being compared to a smoothed and decimated version of itself.

Radiance scaling

The mesh was examined in the *MeshLab*[7] software using the common practice of relighting the model and using radiance scaling to enhance the curvature [6, 17, 19–21]. This works in a similar way to shadow and relief marks in aerial photography and raking light photography in rock art, where the low angle of the light highlights subtle features, with the added functionality of being able to interactively move the light. This workflow made use of the high-resolution model (Fig. 4).

Radiance scaling in *MeshLab* is activated under the render menu, then shaders, and radiance scaling. It is then operated using a simple slider bar to adjust the intensity of the effect. A large portion of the carvings were visible on the model, but the radiance scaling value maxes out too low, and would have produced a better result if more contrast could be added. Lambertian radiance scaling

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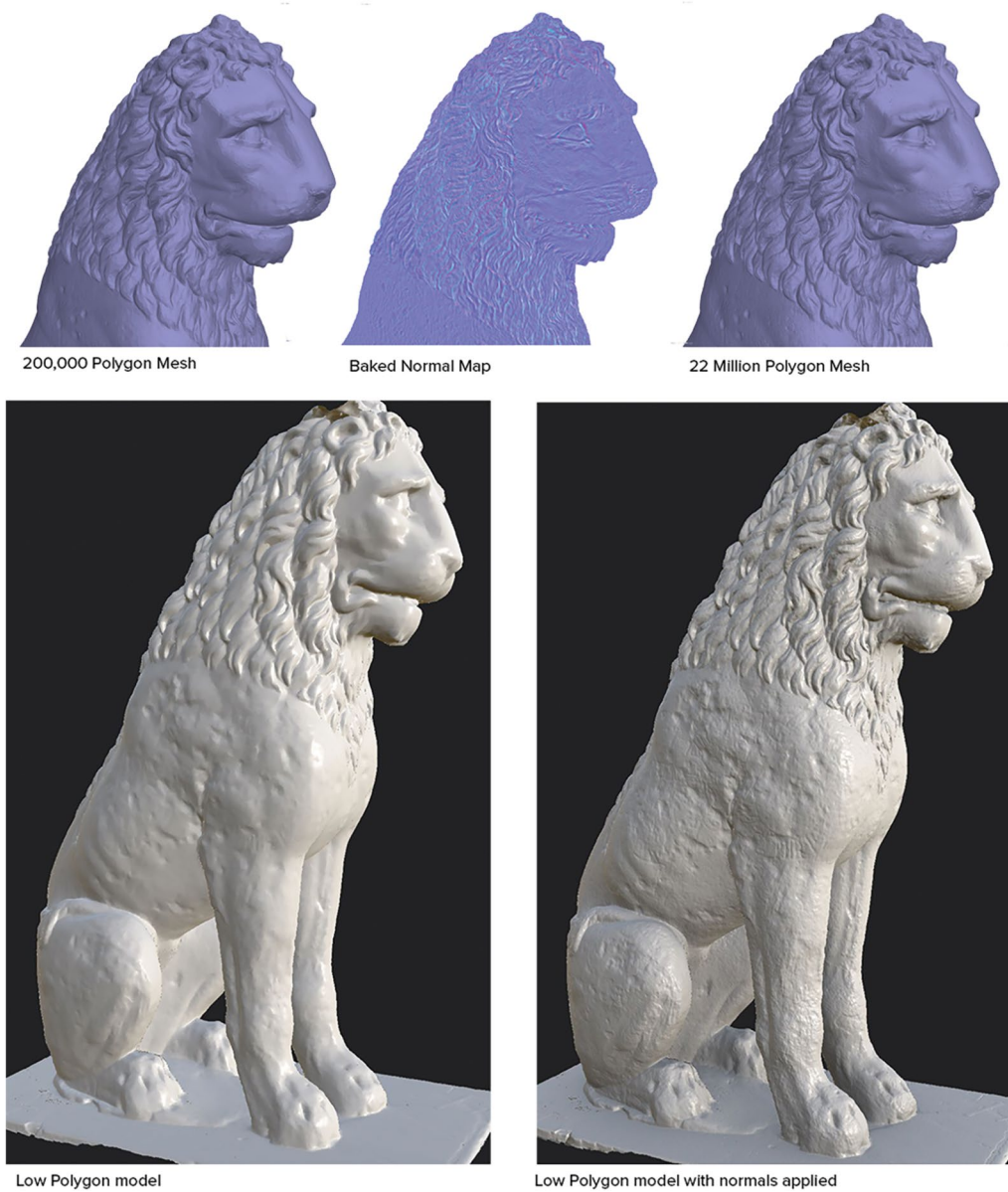
**Fig. 3** Illustration of the outcomes of baking the textures

worked best here with grey descriptor a close second. To improve visibility, colour textures should be turned off [38].

Local Relief Modelling (LRM)

A segment of the model was exported from *Agisoft Metashape* as a DEM (Digital Elevation Model) and processed using the Local Relief Modelling (LRM) method [39], previously described in its application of rock art by Horn et al. [7] and similarly, though under a different name, by Trinks et al. [40]. In essence, a DEM is produced, exported to a GIS software where it is smoothed (Focal statistics in *ArcGIS*, r.neighbors in *QGIS*) and then the result is subtracted from the original DEM (Minus in *ArcGIS*, Raster Math in *QGIS*). This can also be achieved by simply using the local relief tool in the *Grass* addon in *QGIS*.[8] Although this method does not work with full 3D models, this segment was used as a base point to confirm that the results that were produced in the other methodologies presented here were comparable to other established methods (Fig. 5). This process is also possible to achieve in standalone software such as the LiDAR

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[8] https://grass.osgeo.org/grass82/manuals/addons/r.local.relief.html accessed 12.07.2023.
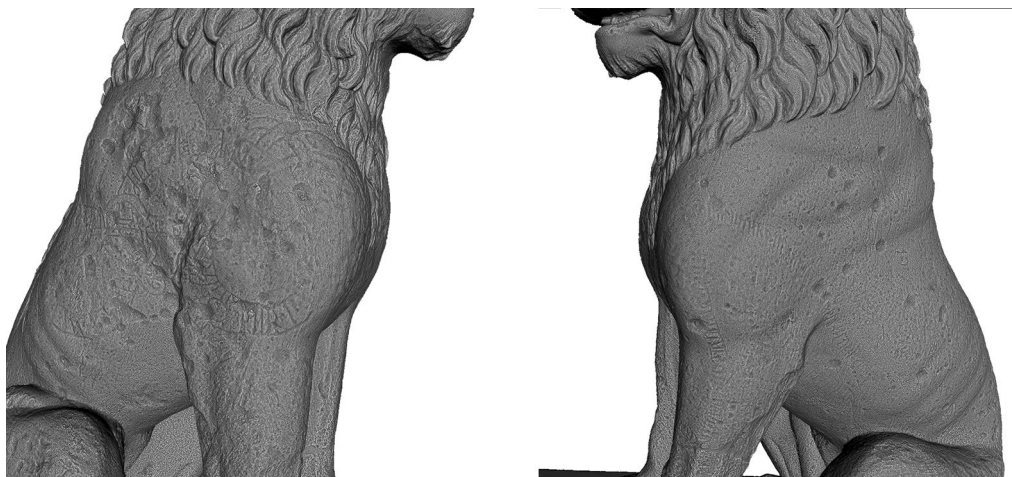
Fig. 4 Lambertian radiance scaling in MeshLab with enhancement set to 1.0 showing the two carved areas of interest on the high-resolution model

Visualization Toolbox[9] and the Topography Visualisation Toolbox.[10]

While the results are a good representation of the carvings, they suffer from the non-planar nature of the object. Since the surface features significant curves the distribution of the scale of shading in the carved areas is minimal, as the height difference between the carved and uncarved surfaces is low.

Agisoft metashape displacement mapping
Agisoft Metashape 2.0 allows for the creation of displacement maps that are UV mapped to the object. A displacement map is created by comparing a high-resolution model to a smoothed low-resolution model and determining where differences in height exist. This then creates a greyscale colour map showing height (Fig. 6).

This was tested using various resolutions, the best results coming from the medium-resolution polygon model, decimated to 50,000 polygons, smoothed three times, and then a displacement map baked to a single 16,834 by 16,834 pixel map within *Agisoft Metashape*. This was then run through the LRM process as described above. Unfortunately, while from a distance it produced good results, zoomed in the results were quite poor. It may be that there are better variables available (i.e. percentage to decimate to), but as yet the documentation gives no indication as to what they are.

Morphological Residue Modelling (MRM)
Morphological Residue Modelling (MRM) is a method in which the model is decimated, smoothed,[11] and then compared using the distance from reference mesh filter in *MeshLab* [13–16]. The smoothed and decimated model removes the smaller carvings creating something akin to an averaged mesh. When this is compared to the original mesh the areas that are carved are now in a different position and are thereby highlighted by the filter.

In this test the high-resolution mesh was decimated (simplification: quadric edge collapse decimation) to around 10% of the original polygon count (nine million polygons), then smoothed using Laplacian smooth with 30 steps. The models were then passed through the distance from reference mesh filter with the default distance value (Hausdorff distance can also be used with similar results [17]. The low-resolution model was used as the measured mesh, with the high-resolution mesh as the reference mesh. Once the process had completed the quality mapper was opened and the histogram altered as required (Fig. 7).

The carvings were highlighted quite strongly, but the shallower carvings suffered somewhat. It was also possible to present the results in a variety of colour schemes, should accessibility issues arise.

Algebraic Point Set Surfaces (APSS)
Algebraic Point Set Surfaces (APSS) rely on smoothing a copy of the mesh, and then mathematically comparing

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[9] LiVT website: http://www.arcland.eu/outreach/software-tools/1806-lidar-visualisation-toolbox-livt accessed 12.07.2023.

[10] Topography Visualisation Toolbox website: https://tvt.dh.gu.se/ accessed 12.07.2023.

[11] Smoothing refers to the removal of sharper edges by a variety of techniques including the averaging of normals. This often reduces the size of the dimensions of the model slightly, which allows differences to be highlighted between smoothed and unsmoothed models.

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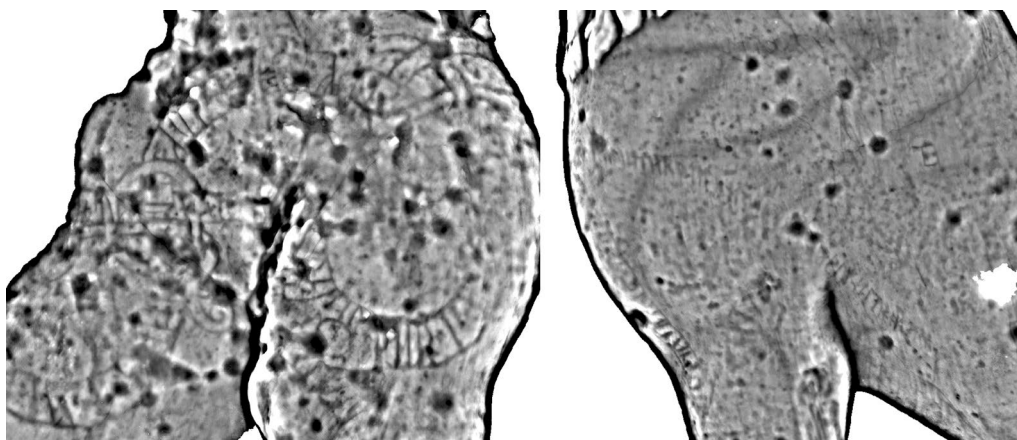
**Fig. 5** Example of the carved areas demonstrated by using LRM
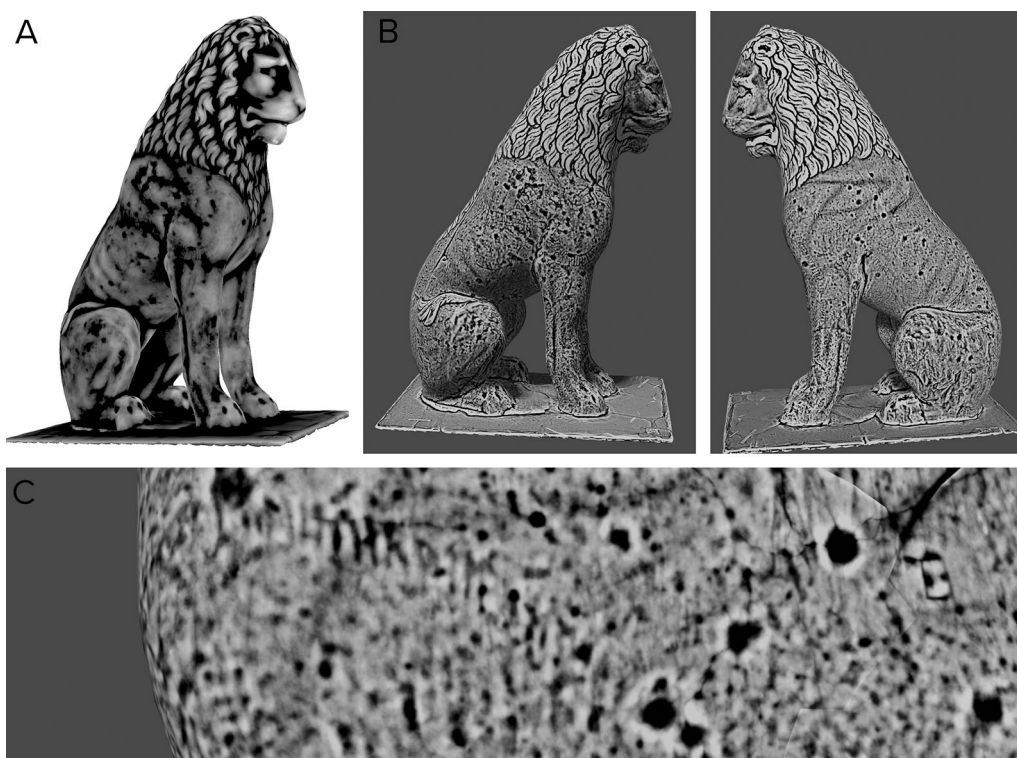
Fig. 6 **A** The raw displacement map shown on the model in Agisoft. **B** The LRM processed displacement map presented in Blender. **C** A close up of the carving showing that, while still largely readable, detail is lacking

the original model versus the smoothed model using a "floating sphere" [41, 42]. The size and accuracy of the sphere can be modified to vary the result. APSS visualisations are created in *MeshLab* using filters, colour creation and processing, and then colourize curvature (APSS). The colour histogram is then amended in the quality mapper until the carved areas are highlighted appropriately [17].

For this test, the medium-resolution model was used, as the processing of the high-resolution model took over 24 h to process, and the histogram became unresponsive due to the file-size. Using the default settings (although a number of other less successful tests were also undertaken) the carvings became fairly visible, with the advantage that it was possible, as with MRM, to adjust the

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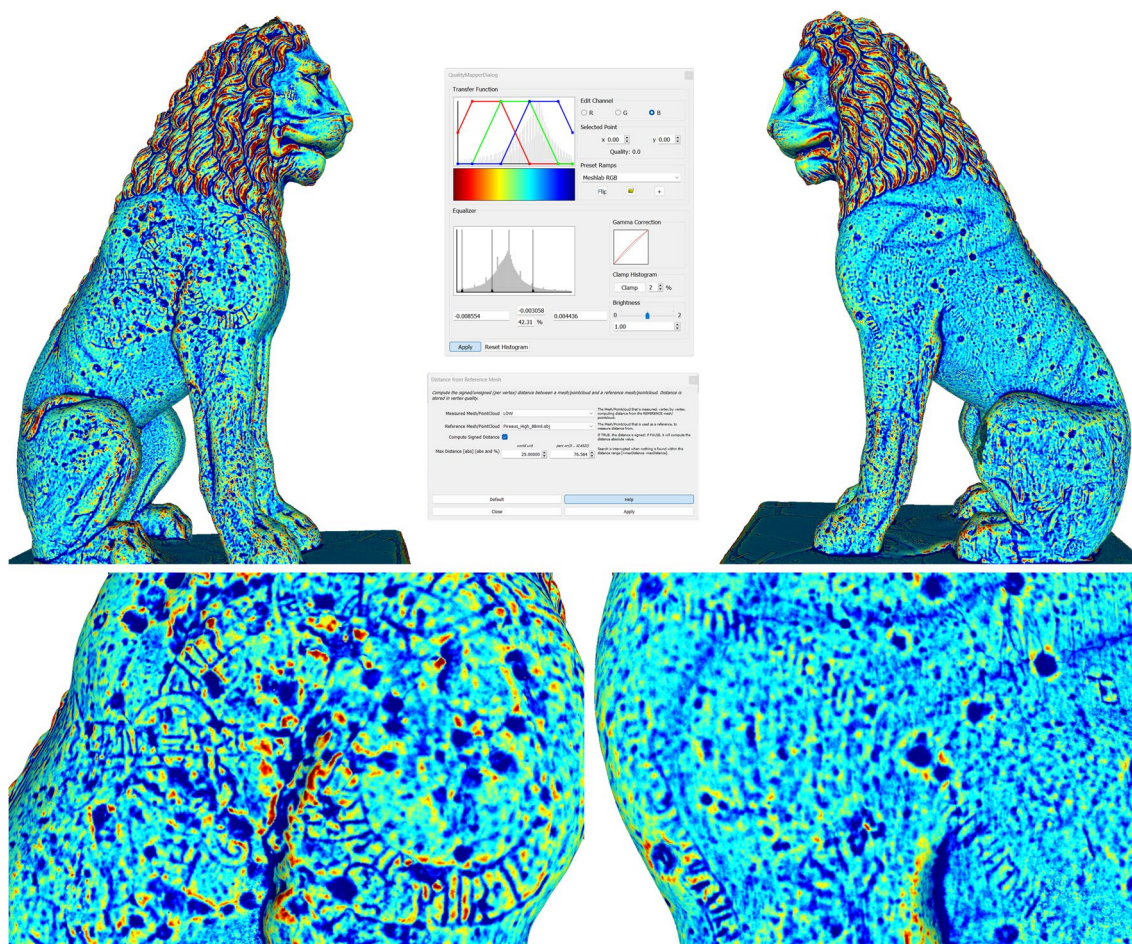
Fig. 7 The result from the MRM with closeups of the carvings at the bottom. The settings used for filter are in the middle

histogram interactively depending on the carving depth (Fig. 8).

It was slightly problematic that the areas with greater curvature, i.e. the mane, gained stronger highlights than the lesser curved areas, which, as shown above, seems to be an intrinsic issue with several of the methods. The carvings were highlighted quite strongly, but the shallower carvings suffered somewhat. Again, the results can be shifted into a variety of colour schemes, for accessibility or preferential reasons.

The APSS processing was rather slow -with some iterations taking several hours to run, and often produced results that were unusable due to the histogram being too spread out to get a good colour separation.

Xshade

Xshade[12] is a free open-source software which has successfully been used in the past to highlight details on models of carved objects [6, 17]. However, it is now showing its age, with its last update in 2011.[13] As such, it is 32-bit architecture only and unable to load larger models. At the time of writing, the latest version of the software did not work, but the older 1.0 version did. The software is run by dragging an.obj file onto the *xshade-make.exe* file to produce an.xsh file, which is then opened by being dragged onto the *xshade.exe* file. Both processes can alternatively be operated using command prompt and opening the.exe file and amending the file name (i.e. xshade-make.exe model.obj). This makes it possible to record the time it takes for each smoothing step and find the limits of the process.
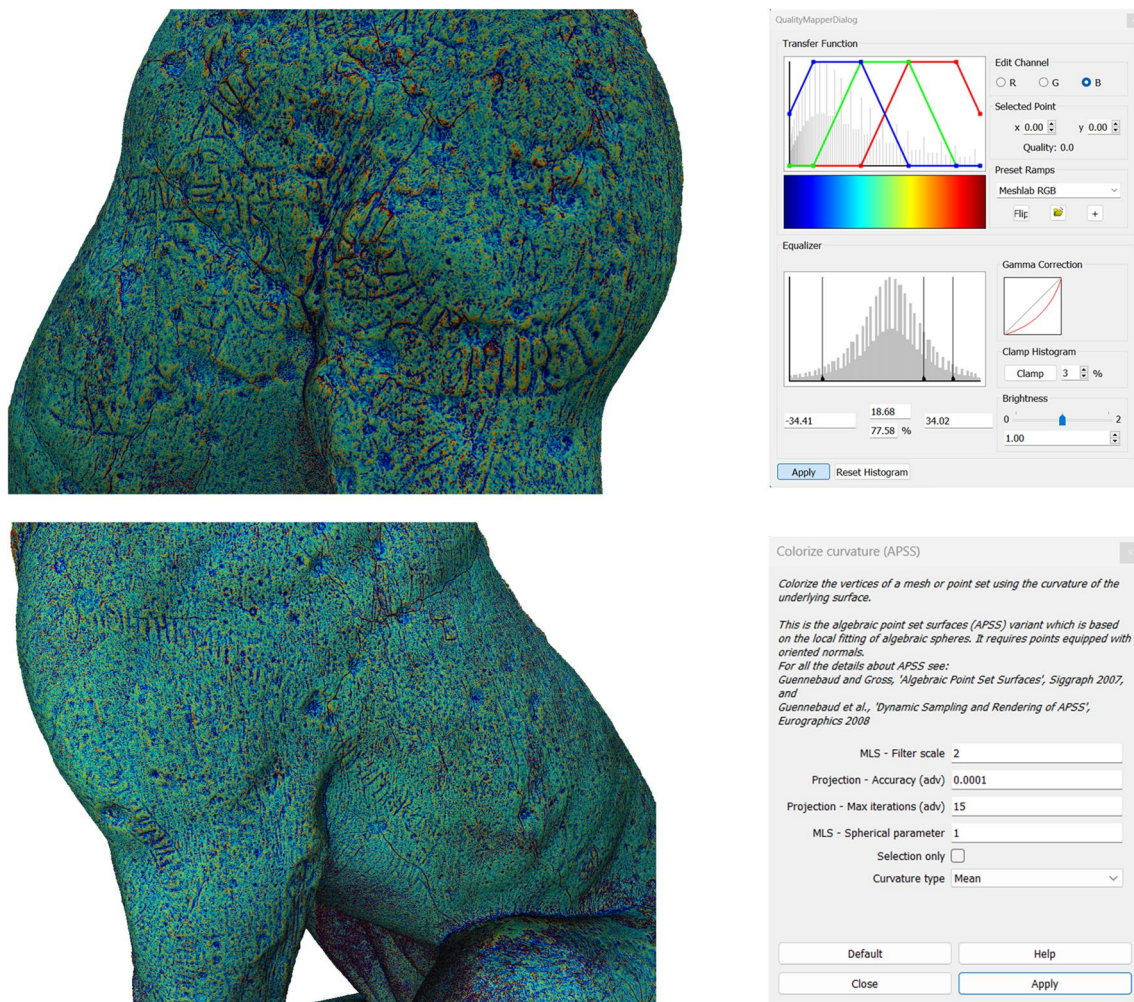
Fig. 8 The results and the settings of the APSS tests

A series of tests seemed to place the limit of polygons at about six million polygons, far below both the medium- and high-resolution polygons in the lion models. This meant that only sections of the lion were able to be analysed at any given time at a high-resolution. Processing the.obj files into.xsh files took approximately two hours, but were quick to open in *Xshade*, and smooth to operate, though higher polygon models exhibited some movement lag.

While *Xshade* produced quite readable results, portions were not particularly clear, especially on areas that had shallow details (Fig. 9). For further testing, a scaled down six million polygon model of the full statue was tested, with the results presented below (Fig. 10).
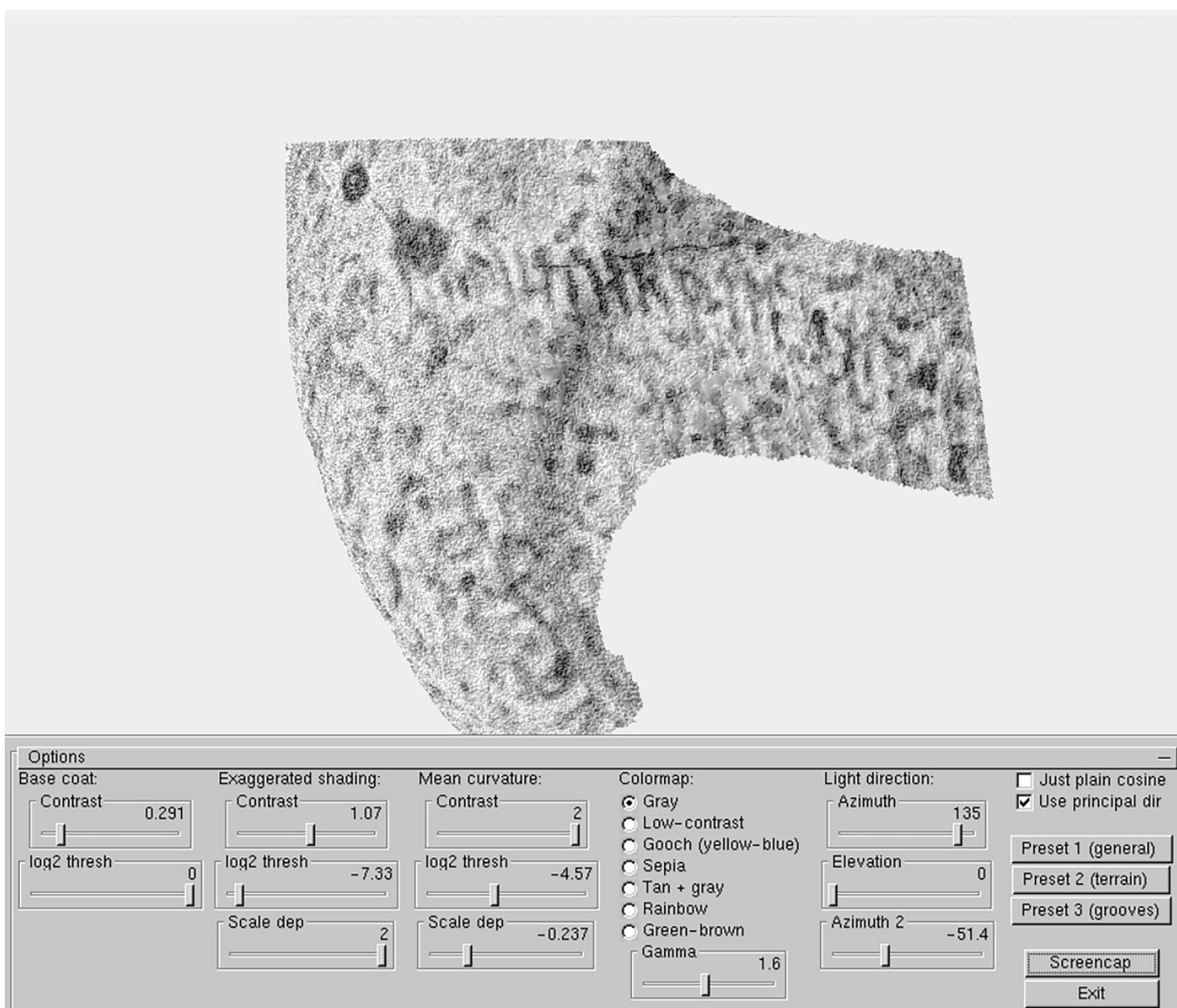
Although the inscription is rather easy to see when zoomed out, closer inspection shows that details are lacking due to the low-polygon nature of the model.

Blender

Blender[14] is a free, open-source 3D modelling software package which has a raft of extra functionality. In the first instance, the visualisation technique was kept as simple as possible. The model was loaded, and then the viewport method was set to solid shaded. Within the viewport settings, the cavity option was enabled with the cavity type set to both world and screen space. The values were then adjusted upwards until the carvings became quite visible (Fig. 11).

Additionally, a second test took place, in which the model was given an empty texture, then nodes were added to the shading graph. In this case a geometry node with the pointiness output connected to a colour ramp node. The colour ramp, which was connected to the base

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[14] https://www.blender.org/ accessed 12.07.2023.

Fig. 9 The results form Xshade on a segment of the lion

colour output of the main shader was then adjusted until the carvings and lower details became visible (Fig. 12).

The process was very quick, with the majority of the time spent loading the model. While it worked with the high-resolution model, it was much easier to work with the medium-resolution model in this instance.

Substance Painter

There are two possible methods using *Substance Painter*. The first method used the high-resolution mesh baked down to the low-resolution model. Within *Substance Painter*,[15] the low-resolution mesh which, as described above, had already been UV-mapped in *Agisoft*

Metashape, was imported, and then texture maps (i.e. normal maps, curvature maps, thickness maps, etc.) were baked to the mesh from the high-resolution model (Fig. 12). Once the maps were baked (at 8192 by 8192 pixels), a fill layer was added, and then the curvature map was used as the albedo (colour) for this layer. This was then enhanced via a levels histogram editor (Fig. 13).

Within *Substance Painter*, details were highly discernible relatively consistently across the model (Fig. 14). While there is a lot of 'noise' (non-inscription details, such as scratches and dents), it was still quite possible to discern individual runes in the model.

The second method only used the medium-resolution model. This method is largely the same, with the model first being imported, and then textures being baked to the mesh at 8,192 by 8,192 pixels, but this time without adding a higher-resolution model: the mesh is instead baked

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[15] https://www.adobe.com/products/substance3d-painter.html Accessed 15.08.23.
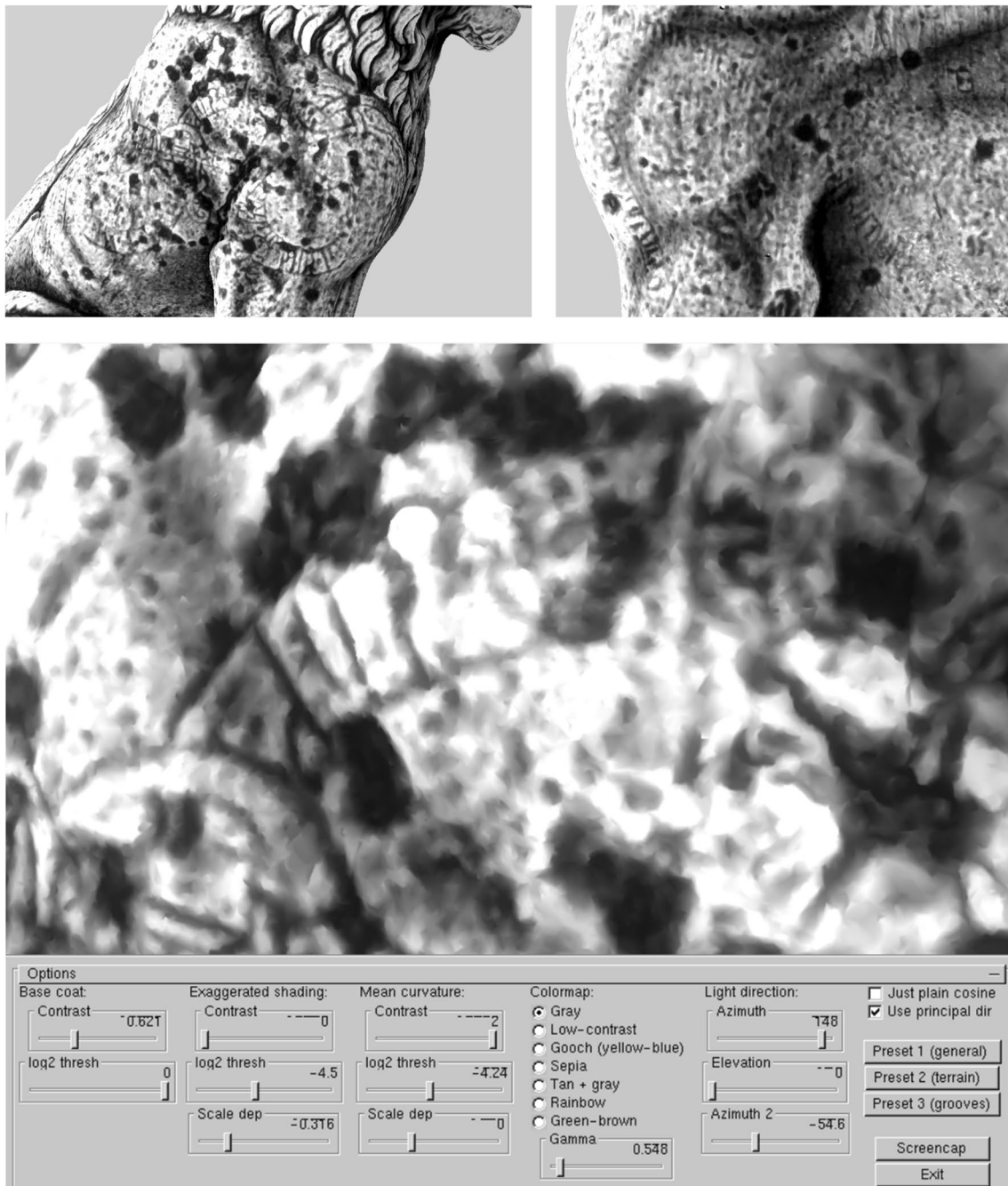
Fig. 10 The results from Xshade on the complete six million polygon model. The close up of the carving shows the lack of detail. The settings used for all visualisations here is shown at the bottom

to itself. The same fill layer populated by the curvature map was used and again enhanced by the levels histogram editor. The results were highly comparable to the baked low-resolution model, but seemed to have more peak areas than the low-polygon model (represented by the white areas on the model, Fig. 15).

Since one of the main functions of *Substance Painter* is for 3D artists to paint on models, it is also possible to annotate and apply interpretations directly to the model non-destructively (i.e. they are saved on layers that allow you to turn them off when required, Fig. 16). This can then be baked out as a high-resolution map (8,192 by

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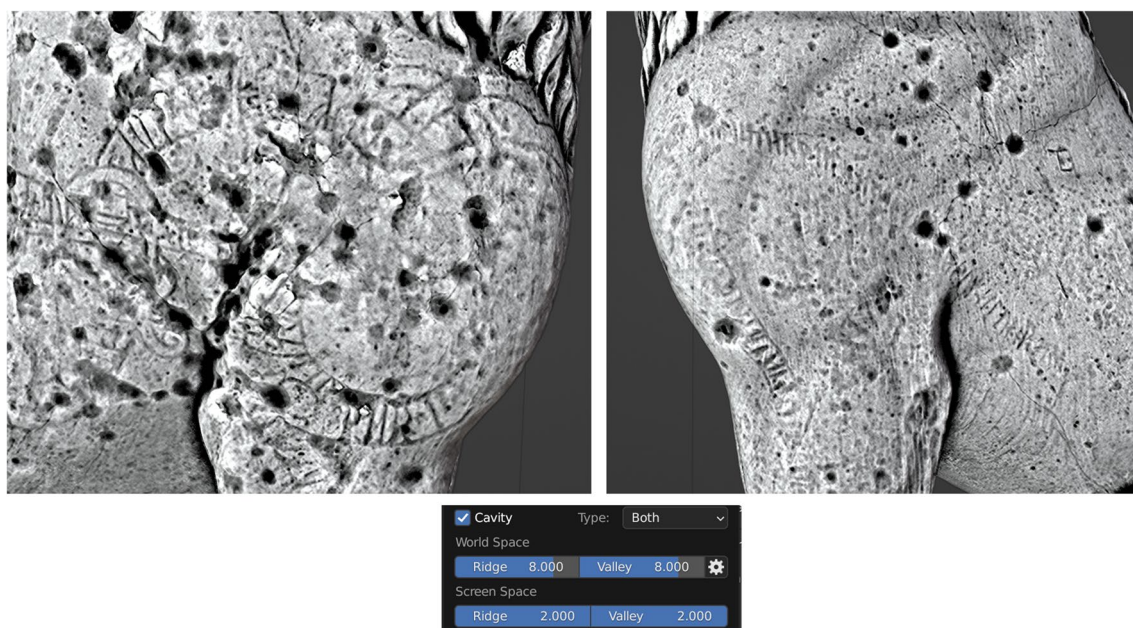
Fig. 11 Output from Blender using the cavity enhancement with settings shown below with the medium-resolution mesh

8,192 pixels) and shared as an entity for analysis in any software that can open 3D models with textures.

A further benefit of the *Substance Painter* workflow is that since the low-resolution model obtains similar levels of the curvature details to the high-resolution model, without the difficulty of having to work with a high-resolution model, it allows for the sharing of the mesh with those that do not have the possibility to use powerful hardware. Its smaller file size also makes sharing the model easier due to potential bandwidth issues. While this makes sharing easier, it must also again be stated that the low resolution model does not retain accurate measurements or micro-topographical geometry on the 3D model.

Substance painter also allows for the creation of "smart materials", which are essentially custom presets within the software. These allow the user to recreate the process above on other 3D models without having to go through all of the setup steps. It still maintains the functionality of being able to adjust the parameters (i.e. the levels histogram) and to add other filters if required, but makes it much easier to recreate results and process multiple models quickly.

Mari

Within *Mari*,[16] a colour layer was added as a base layer of a very light grey, followed by two curvature nodes, one set to convexity, the other to concavity. This was then followed by a levels layer and a brightness layer to allow for manual adjustment to enhance contrast in the result (Fig. 17). The textures were created at a size of 16,384 by 16,384 pixels to get the highest possible resolution and to show the greatest number of details.
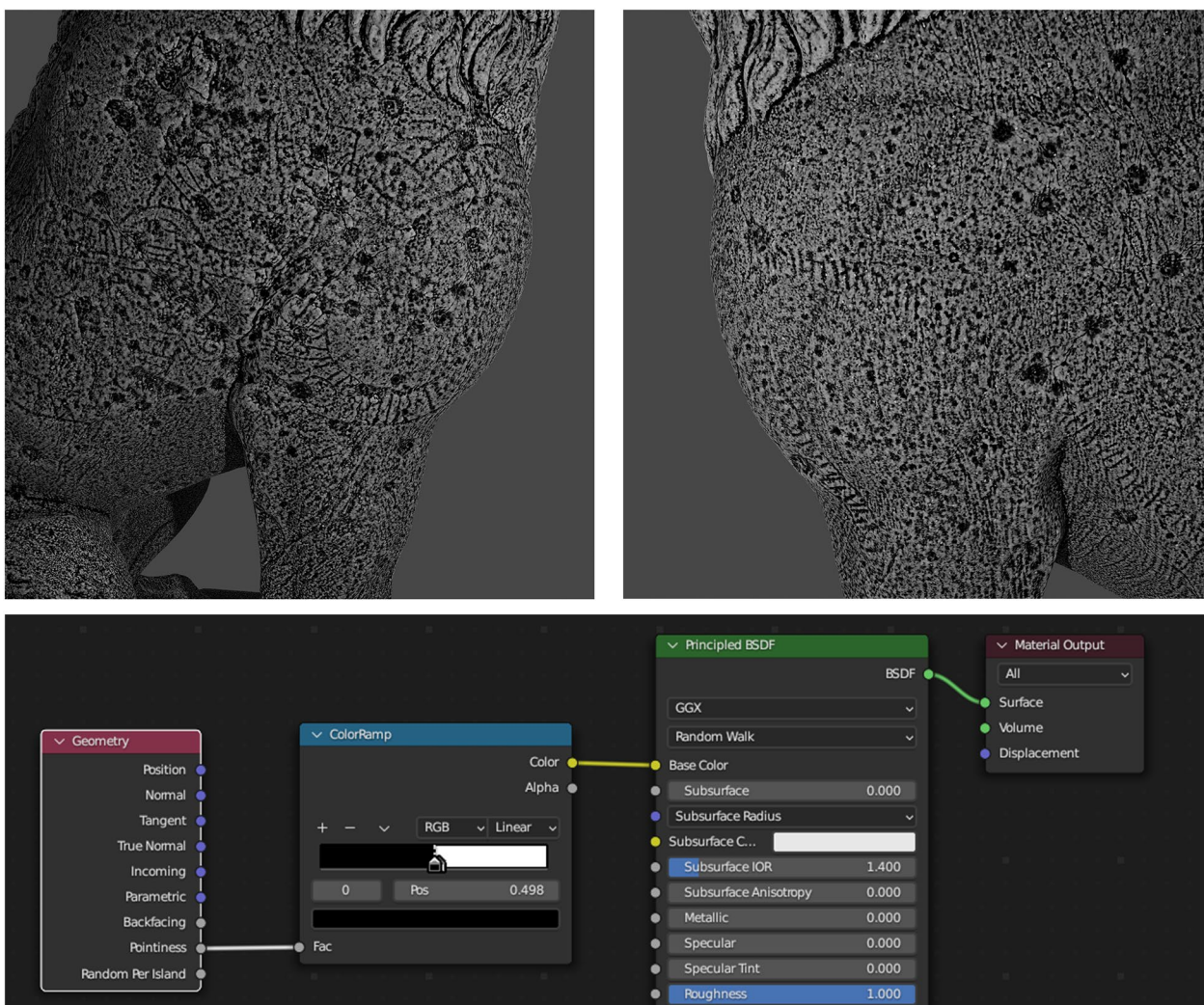
Mari created too much "noise" to delineate the carvings in some places, particularly when viewing the mesh from further away. However, upon moving closer to the mesh, the carvings become somewhat clearer (Fig. 18).

The *Mari* user interface is rather more complicated and less intuitive than *Substance Painter*, though it does seem as though it could potentially be the more powerful alternative in the long run, especially since it allows for the creation of higher resolution texture maps (one of the key reasons for including Mari in these test). While Mari was able to run the high-resolution mesh and create higher resolution textures, this does come at a cost of requiring higher performance hardware.

Discussion

Using SfM as a documentation method overcomes several of the difficulties regarding first-hand readings of the inscriptions, including the inaccessibility of the sculpture (located in a naval base), the translucence of the material, and the sheer size of the monument. As the recorded model is completely digital, it is also possible to disseminate copies to researchers for comparisons of interpretations or application of further experimental techniques.

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[16] https://www.foundry.com/products/mari accessed 15.08.2023.

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**Fig. 12** Node graph from Blender and the result from both sides of the medium-resolution Lion

Another strength of the recording method is that no specialised equipment is strictly necessary, with regular digital cameras and reference cards covering all needs. The relatively low cost of the software and the accessibility of tutorials and user guides add to this, making the method versatile for the recording of inscriptions on a great variety of surfaces and materials.

The majority of the software used to create the visualisations presented here was generally relatively easy to use (though a number of issues arose from outdated software and file sizes), with very little effort required to obtain results once the methods were understood. In the case of *Substance Painter*, after the fill layer with the curvature and levels histogram was added, it is possible to create a template 'smart material' meaning that it could easily be applied directly to other models without needing to repeat the steps again. Along with the model, this smart

material can be disseminated to other researchers, who would then be able to accomplish the same results consistently. Table one presents an overview of the above, as well as some of the benefits and pitfalls that each method has.

Using the aforementioned LRM method as an additional control step, it became clear that *Substance Painter* also highlights carvings reliably in rock art panels (Fig. 19). However, in the case of *Mari*, it was again evident that it was almost too detailed, meaning the carvings were less visible. The adjustability of *Substance Painter* also meant that it was easier to isolate the carved areas.

But how did *Substance Painter* compare to the other methods? In general, it produced a largely comparative or better result than the other methods (see Table 1). While the radiance scaling method produced a very good result,
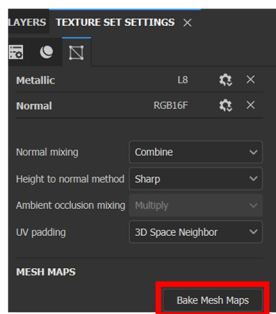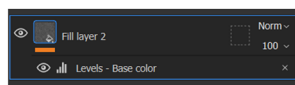
1. Bake Mesh Maps selected
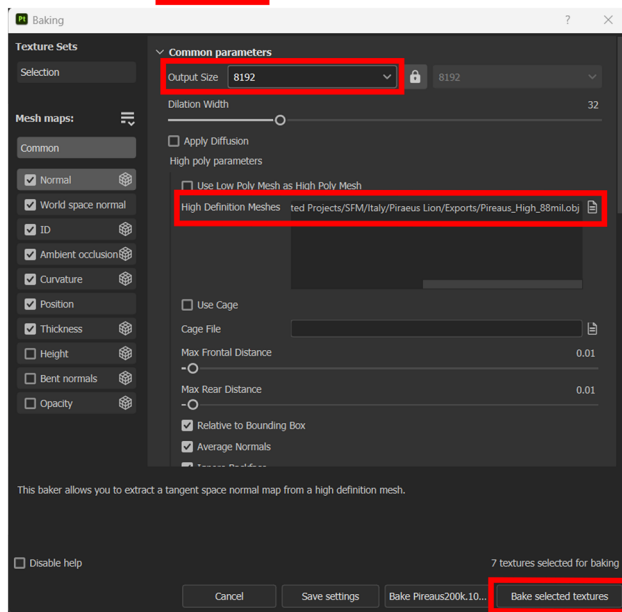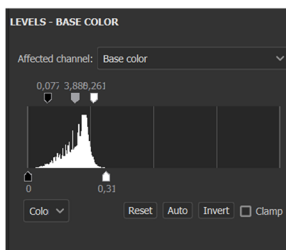
2. Output size set to 8192 x 8192 pixels

3. High defintion mesh selected

4. Selected textures baked

5. Fill layer added with curvature map
6. Levels added

7. Levels histogram adjusted

**Fig. 13** Workflow of the Substance Painter method

it was limited by how contrasted it was, meaning that some of the shallower carvings were less visible (although still visible). This issue was solved by using *Blender*'s viewport shading which creates a similar effect but allows for ramped up values. However, neither of these methods produce texture maps which can be passed on to other researchers as they only produce temporary effects.

While they are quite easy to reproduce, for someone with no experience they can be a challenge.

Blender's texturing method using pointiness does allow for a texture to be produced, as well as both *Substance Painter* and *Mari,* but in this respect, *Substance Painter* is by far the easier method as there are significantly fewer

Fig. 14 Results from Substance Painter using the curvature method on the low-resolution model with the high-resolution model baked down to it
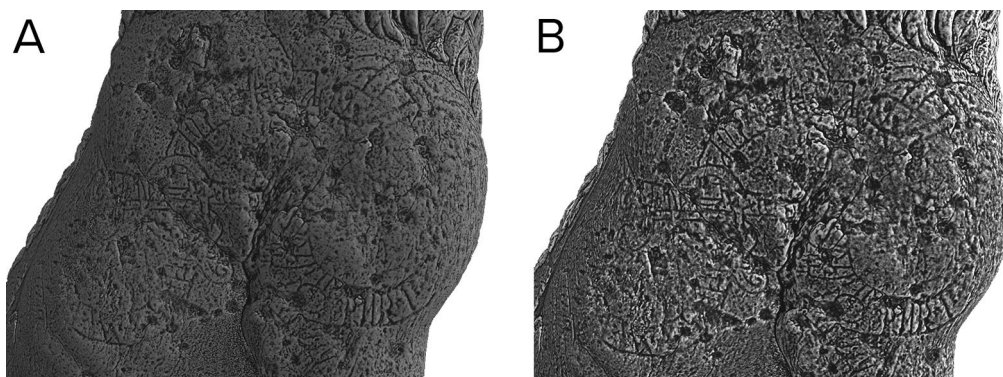
Fig. 15 Comparison between the low-resolution baked model (**A**) and the medium-resolution polygon model (**B**) after processing in Substance Painter

steps required, and the texture baking process is much simpler.

MRM and APSS were both quite suitable methods for this kind of work, as has been shown in the past. However, the methodologies required quite a significant amount of testing before they produced results, largely because there is so little published about how to actually run the processes. While the results are good, the processing times were high, and the histogram in *MeshLab* is not the most intuitive, stable, or user-friendly tool.

Xshade was limited by its capability to handle larger scale models, and while producing pleasing results from afar, the details were lacking when zoomed in. The same problem existed for displacement mapping in *Agisoft Metashape*, despite it being an adapted version of the LRM methodology.

In general, the high-resolution model proved difficult to work with in terms of processing time and moving the model to inspect different areas. The difference between the high- and medium-resolution model only varied a little, so it was not considered to be a major problem to proceed with the medium-resolution model, especially for these types of visualisations. The possibility of working with a small model, for example the low-resolution model created for *Substance Painter*, was preferable in terms of processing time, dissemination, and generally moving and rotating the model.

Substance Painter, *Mari*, and *Blender* all include the possibility to paint interpretations directly onto the model in a non-destructive fashion. This is a very useful feature since these annotations can then also be shared with other researchers. The was again more intuitive in *Substance Painter* than any of the other software.

While it is acknowledged that the majority of the methods presented here use free software, and *Substance Painter* and *Mari* are tied to subscription licenses, for the most part the cost of these licenses, particularly for educational facilities, is not overwhelming.

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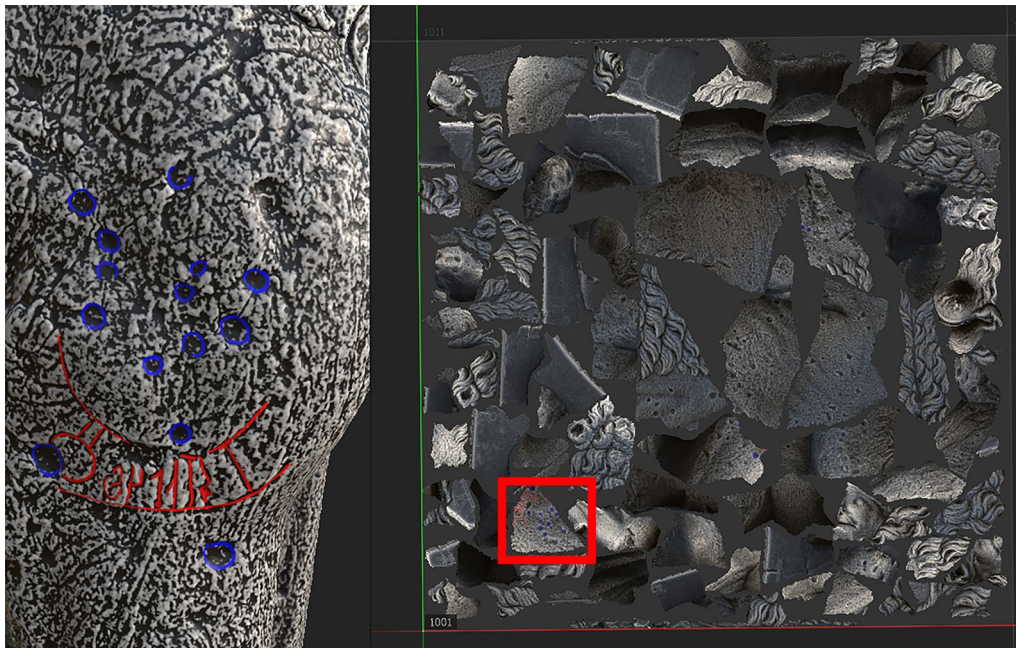
Fig. 16 Direct painting onto the model in Substance Painter with blue to denote damage and red to denote carvings. The image on the right the represents the UV map, note the highlighted section in the lower right, where the annotations are stored
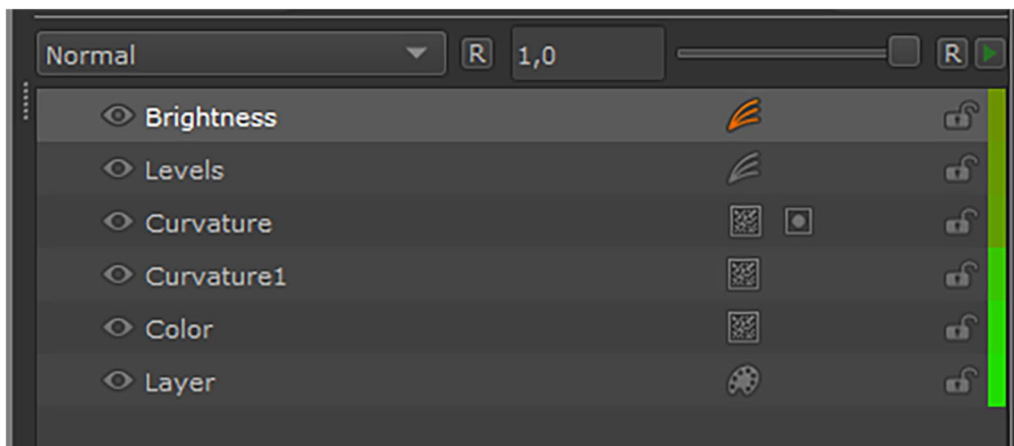

Fig. 17 The layer set up used in Mari

It was noticeable that all of the methods had their own individual strengths and weaknesses in various areas of the model. Most often, they struggled with areas that had less distinct carvings, particularly those on the sculpture's left-hand side. With the exception of APSS, both *Substance Painter* and Mari seemed to handle larger topographic variations in the sculpture better than most of the other methods, which seemed to highlight the larger contours. In this instance increasing the visibility of the larger contours was undesirable as it obscured the smaller carvings.

Overall, while both *Mari* and *Substance Painter* provided useable results, it was clear *that Substance Painter* was the better option of the two, both in terms of visibility of carvings, and ease of use. While the results were highly comparable to the other known processes in terms of highlighting carvings, *Substance Painter* provided a significantly quicker and more intuitive experience. The possibility to use a low-resolution model that
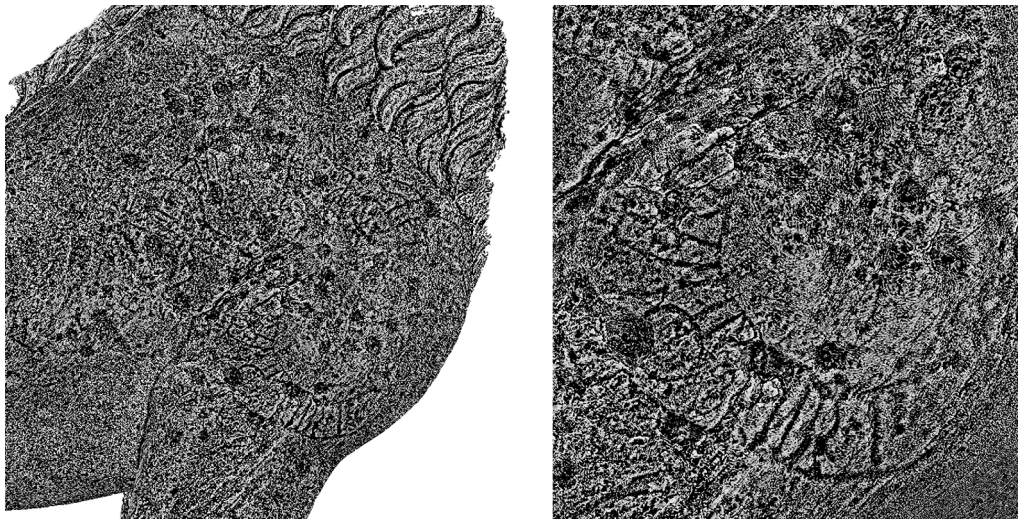
Fig. 18 The Results of Mari on the high-resolution mesh demonstrating that the level of noise detracts from the carvings

Substance Painter   LRM Method   Mari
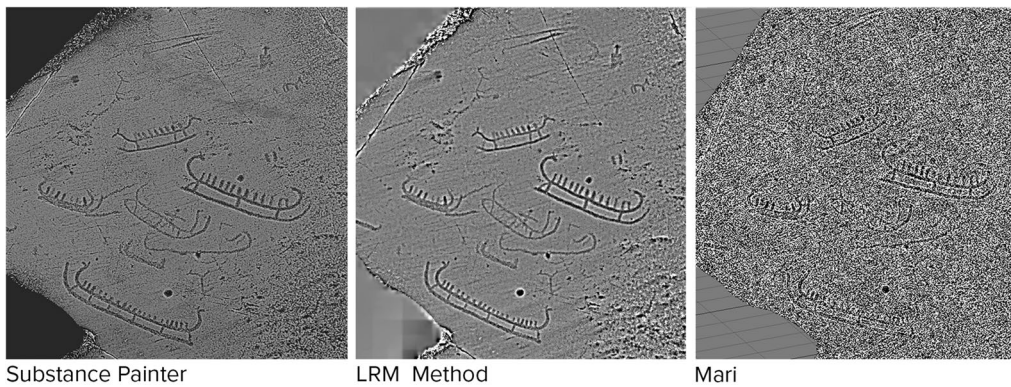
Fig. 19 Comparative verification step using an SfM of Brastad 5:1, a rock art site from Tanum, using Substance Painter, ArcGIS and the LRM Method, and Mari

can be disseminated with an annotated texture map is something that none of the other established methods can produce. Being able to share a "smart material" from *Substance Painter* also increases the reproducibility of the results.

While the low-resolution method does remove the 3D detail of the model, it allows for those with less hardware capabilities to both inspect, annotate, and view the entirety of the carvings in their original position and in the context of additional carvings around it. It also allows for the discovery of new carvings in areas that may not ordinarily be focused on, which can then be analysed in more detail using trimmed sections of the mesh with other methods. The high-resolution method retains all the original 3D information of the original mesh, but requires access to more powerful hardware.

Once the mesh is exported from *Substance Painter* it can be used as any other 3D model would be used, for example, for publication on Sketchfab, with its annotated surface as an additional layer of interpretation alongside the photorealistic texture. It is also possible to relight the carvings both with HDRI maps, and by rotating a light in *Substance Painter*.

The presented results have also shown that both *Mari* and *Substance Painter* are capable and useful tools for the initial investigation of carved surfaces, as well as for producing visualisations of carvings for dissemination.

As previously stated, no one method is a 'magic bullet' for uncovering all the information about any given carving [13]. It is worth restating that we do not advocate or present the use of *Substance Painter* or *Mari* as a method to be used at the exclusion of others, but instead

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Table 1 Table showing the results and outputs of the tested methods

Method	Processing time	Full 3D model	Open source /free	Ease of using process	Output	Temporary or textures producible	Highest model level method worked with
Blender Viewport	Minutes	Yes	Yes	Simple, blender handles large models very efficiently	Carvings highly visible, but only a temporary lighting effect	Temporary	22 million
Blender Pointiness	Quick depending on hardware	Yes	Yes	Some effort required to set up nodes and adjust values. Requires powerful hardware depending on model size	Carvings highly visible, but user interface is complicated and node production is not the most intuitive to adjust	Textures maps producible	22 million
Substance Painter	30 min, mostly loading/baking time	Yes	No	Several easy steps,	Carvings highly visible, easy to adjust variables. Some learning curve to run process, but possible to make a "one click" smart material	Textures producible	88 million
Mari	30 min	Yes	No	Several steps, not the most intuitive to set up	Carvings are visible, but there is a lot of noise which makes them harder to see. High possibility to adjust variables	Textures producible	88 million
Xshade	Several hours	No	Yes	Easy once you understand the instructions. requires some knowledge of handling/splitting models	Poorly visible carvings due to necessity of low resolution of the mesh	Temporary	6 million
MRM	Under an hour	Yes	Yes	No known parameters make it difficult to get a good result	Carvings highly visible, but histogram in Meshlab is rather unintuitive to change variables. Larger curves are highlighted more strongly, which can have a negative effect on small carvings	Temporary, but saveable	88 million
LRM	Quick	No	Yes if using *QGIS*	Requires some GIS software knowledge, and handling/separation of 3D models	Carvings visible, but heavily affected by large undulations. Only works on one plane	Only a 2D surface produced	N/A
APSS	Several hours	Yes	Yes	Lots of trial and error, histogram produced is potentially unusable	Carvings are highly visible, but method takes a long time to process, especially on higher resolution models. Histogram in Meshlab not the most intuitive to work with when changing variables	Temporary, but saveable	22 million

Table 1 (continued)

Method	Processing time	Full 3D model	Open source /free	Ease of using process	Output	Temporary or textures producible	Highest model level method worked with
Radiance scaling	Quick, most time spent loading model, and moving into place	Yes	Yes	Easy, with a high-polygon mesh navigating round the model and moving lights etc. is a slow process	Carvings highly visible, but diminished by the low maximum level of enhancement	Temporary	88 million
Agisoft displacement	Relatively quick	Yes	No	Complicated as instructions limited	Has potential, but also requires a large amount of trial and error. Carvings visible but not very clear	Yes	22 million/50 k

as additional tools to aid the process of visualising and interpreting carvings on a 3D model. The best results for any documentation of this kind will always include traditional methods like frottage and tracing, as well as a multitude of digital methods for comparison [29].

Conclusions

This paper has shown that both *Substance Painter* and *Mari* are viable tools for successfully visualising, presenting, and disseminating carvings on different mediums. Comparisons to other established methods have demonstrated that it is possible to gain a reliable impression of small, incised details in stone on full 3D surfaces by using standard 3D texturing methods, with the additional benefit of being able to annotate non-destructively and work with smaller file sizes. Its suitability as a method has also been shown by its ability to bake the curvature of the mesh itself to a texture map, and then dynamically highlight the concave and convex features of the object.

Of the two software presented here, *Substance Painter* and *Mari, Substance Painter* was the most intuitive, easier to work with, and produced more interpretable results in this instance. While there are a host of features available in both *Substance Painter* and *Mari* which will likely further improve the visualisation of the inscriptions, this article has presented a fairly simple and reproducible method.

A full study of the Runic inscription recorded is in progress, and will be presented in a future article. We aim at employing the presented texture-based methods and the results as a starting point for which further experimentation can take place both within this project and others, especially those including rock art and epigraphy.

Abbreviations
MRM   Morphological residual mapping
RTI   Reflectance transformation imaging
vRTI   Virtual reflectance transformation imaging
SfM   Structure from motion
DEM   Digital elevation map
LRM   Local relief modelling
GIS   Geographic information system
APSS   Algebraic point set surfaces

Author contributions
The project was devised by JW and RP. Permits and necessary permissions were handled by JW. Documentation was carried out by RP and RR. Analysis and visualisation were carried out by RP. The article was written by RP and RR with input from JW. All images were prepared by RP. All authors reviewed the manuscript.

Availability of data and materials
Material can be accessed upon request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
There are no competing interests to declare.

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