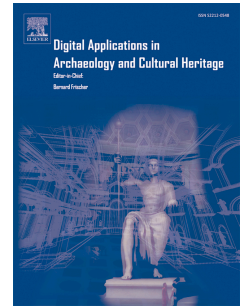


# Accepted Manuscript

Lost colours: Photogrammetry, image analysis using the *DStretch* plugin, and 3-D modelling of post-firing painted pottery from the south west Iberian Peninsula

Esther Rodríguez González, Sonia Carbonell Pastor, Josep R. Casals



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Esther Rodríguez González – Institute of Archaeology (Spanish National Research Council-Regional Government of Extremadura)

esther.rodriguez@iam.csic.es

Plaza de España, 15

06800 – Mérida, Spain

Sonia Carbonell Pastor – University of Alicante

[sonia.carbonell@ua.es](mailto:sonia.carbonell@ua.es)

Department of Prehistory, Archaeology, Ancient History, and Greek and Latin Philology. Faculty of Philosophy and Literature II.

Ctra. San Vicente del Raspeig s/n

03690 – San Vicente del Raspeig (Alicante), Spain

Josep R. Casals – Art & Design

jrcasals@gmail.com

C/ Numancia nº84 5º 1ª 08029 Barcelona

## Lost Colours: Photogrammetry, Image Analysis using the *DStretch* Plugin, and 3-D Modelling of Post-Firing Painted Pottery from the South West Iberian Peninsula<sup>1</sup>

Abstract: The main purpose of this project was to verify the use of the *DStretch* plugin, designed to study rock art, for analysing post-firing painted pottery from the Late Bronze Age and Early Iron Age in the Atlantic façade of the Iberian Peninsula. To do so, a Guadalquivir-type carinated pot was used as a study vessel from the excavations of Portaceli (Medellín, Badajoz, Spain). The study brought together all of the different methods used, from the photogrammetry used to obtain a high-quality image of the piece, analysis with *DStretch*, and the final 3-D modelling process in order to accurately reproduce the shape and decoration of the vessel. The final goal was to obtain precise documentation on these types of vessels, the handling of which is not recommended due to the fragile nature of the pigments used in their decoration.

Key words: Bronze Age, Iron Age, RGB images, photogrammetry, *DStretch*, pottery

### 1. Introduction:

Post-firing painted pottery is a product that characterises the transition period between the Late Bronze Age and Early Iron Age in the Atlantic façade of the Iberian Peninsula (Celestino, Rodríguez González and Donate, 2018). These are products in which vessels from the Late Bronze Age were used, characterised by being hand-made, fired in a reducing environment, and whose exterior is simply smoothed or brushed, and to which some time later a painted decoration was applied that was typical of the Early Iron Age, as revealed by the geometric elements that characterise it. The influence seen in these decorative motifs comes from the Mediterranean, enhancing the uniqueness of these products, which nevertheless extended along the whole of the Atlantic façade of the Iberian Peninsula, from the central plateau to the Guadalquivir valley. These characteristics make post-firing painted pottery from the Atlantic façade an exceptional item for studying the transition between the Late Bronze Age and Early Iron Age in the south west Iberian Peninsula.

Despite their uniqueness and beauty, these ceramic products suffer from a major problem which has so far hindered their correct study: the preservation of the paint used for their decoration. As this paint was applied after the vessels were fired, it did not attach to the vessel, meaning it comes off in contact with the earth

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<sup>1</sup> This work is part of the R&D&I Project entitled “Building Tartessos: Constructive, Spatial, and Territorial Analysis of an Architectural Model in the Central Guadiana Valley” (HAR2015-63788-P).

or even when touched, making these items extremely delicate and difficult to handle.

The state of preservation of the pots recovered during archaeological excavations is generally very poor, except for those that were used as grave goods. In these cases, the post-depositional processes that affected the vessels were not so aggressive (Torres, 2008). Also, restoring these pieces is a highly complex task, as the application of any type of fixing element would compromise the undertaking of future analyses of the pigments, which would be altered by the chemical element applied to them. As a result, the decoration used on this type of pottery is destined to be lost over time.

Faced with this situation, the fragility of the pieces and the complexity involved in studying them, we propose a working methodology based on image treatment aimed at making it possible to study the decoration on these types of objects. The final goal of this digitalisation process is to be able to design and print 3-D models of the pieces that can be handled without the need to alter the state of preservation of the original item. In doing so, we will open new lines of work aimed at studying aspects ranging from the production processes or the post-depositional processes that most affect their preservation, through to experimenting with restoration techniques which, once they have been proved to be effective, can be applied to the original pieces.

To do so, a novel methodology is proposed that has never been applied to the study of complete ceramic pieces. This methodology is based on three working stages, which begin with the restoration and reconstruction of the piece in the laboratory. One new feature of this methodology is the use of the *DStretch* tool, designed for studying rock art paintings, and which we have used on this occasion to document the decoration that has been lost from these ceramic elements.

## **2. Background:**

The *DStretch* programme was created for use with digital images of rock art paintings. Its creator, Jon Harman, carried out the first trials with paintings from the USA and Mexico. The excellent results obtained led the tool to be applied in numerous study cases (Le Quellec, Duquesnoy and Defrasne, 2015), including examples from South America (Gutiérrez Calvache et al. 2009; Hostnig, 2012;



Acevedo and Franco, 2012) and Spain (Quesada 2008-2010; Martínez Collado, Medina and San Nicolás, 2013), as these are the most numerous.

However, the programme has not been widely used with ceramic elements, which is why this study represents a major innovation. The only study in which the *DStretch* programme has been used with a complete piece is from Mexico (Miller and Thompson, 2015); however, the study did not focus on evaluating the use of this programme in analysing ceramic elements, but instead simply used it as a means of revealing the decorative motif on the pottery in greater detail, as the aim of the study was to carry out a stylistic analysis and to identify similarities with other elements. Similarly, another paper was published a few years ago that referred to the application of *DStretch* in pottery studies, in this case for preventive purposes. The programme was used to identify the deterioration of pottery glazes in pieces from China (Lahlil, Li and Ming Xu, 2013), as the contrast treatment makes it possible to detect the craquelure on pottery surfaces in order to evaluate their state of preservation.

The *DStretch* plugin has only been used with pottery pieces to detect and study pigments on two occasions. The first was presented at the Southwest Symposium of 2016 as a poster. This was an analysis of a small fragment of pottery from the site of South Mountain Regional Park in Phoenix, Arizona, where a series of red lines with different tones are visible to the bare eye (Shepard and Wright, 2016). The aim of this study was for the *DStretch* programme to precisely identify the density of the pigments in the lines on the pottery in order to carry out X-Ray diffraction analyses on them, to determine whether the lines had been made at the same time, and if the pigments had the same composition and origin, despite being in different colours. The second study case is a recently published paper in the *Revista de Arqueología Iberoamericana*, which analyses the use of this tool when applied to painted pottery from Late Prehistory in the south east Iberian Peninsula (Dorado, 2018). This is a brief study, in which pottery from different sites and from different periods was selected, exploring the use of the *DStretch* programme in examining pottery elements decorated with paint or incisions.

Both studies only refer to the use of the tool with small fragments of pottery, although they do represent the start of a new field of analysis which we wish to complete with this study, in which we propose for the first time a methodology for examining complete ceramic pieces.

### 3. The study case:

In order to apply and implement the methodology proposed in this study, we selected a piece of pottery currently included in the protohistory collection from the Archaeological Museum of Badajoz, from excavations carried out in 1988 in the Portaceli site in Medellín (Badajoz, Spain) (Jiménez Ávila and Haba, 1995). This is a carinated pot with an S-shaped profile and a spherical lid, made by hand and fired in a reducing environment, responsible for the black colour of its clay. It has a diameter of 22 cm and a height of 8 cm, with a dome-shaped base (fig. 1).

The first decorative treatment applied to the piece was an all-over burnishing, giving it a metallic appearance. Sometime later, the pot was painted using red pigments; however, the fact that it had been previously burnished seriously affected the adherence of the paint. These types of decorations applied after firing are normally painted on vessels that have simply been smoothed or brushed, as the rough finish helps the paint to adhere. In the case of the vessel from Portaceli, the fact that the paint was applied to a burnished surface means that it has not been well preserved. For this reason, from the range of painted pottery we had available for this study, we selected this piece in particular, as it had already lost most of its painted decoration, and its state of preservation called for an immediate intervention.

The vessel from Portaceli belongs to what is known as 'Guadalquivir-type pottery' (Ruiz Mata, 1993), present in large numbers in the site of El Carambolo in Seville, Spain, which are its item (Casado, 2015). One of the unique aspects of this pottery is the design used for its decoration, consisting of geometric motifs. The space used for the decoration is divided into four quadrants that are decorated using the same scheme, which is why it is relatively easy to identify the design of this pottery even though nearly all of them have lost part of their paint, as with the vessel from Portaceli, as only one of the quadrants needs to be preserved.

### 4. Methodology:

Although a partial illustration of the decoration of the vessel was included in the results of the excavation at Portaceli that were published in the 1990s (Jiménez Ávila and Haba, 1995: 238, fig. 8), the main aim of this study was to recover the lost decoration, in order to discover whether the first illustration was an accurate

representation of the decoration used on the vessel, so that this could then be used in the 3-D model of the piece.

The first tests using the *DStretch* plugin with photographs of the pot provided us with excellent results (fig. 2) although they did complicate the hand-drawn decoration as they only provided a partial view of it. Therefore, with the aim of obtaining a high-quality image that was as vertical as possible, allowing us to focus on analysing the image with *DStretch*, we included the creation of a photogrammetric model as the first step in our methodology.

To do so, we used a Nikon D5600 camera with a Nikon AF-P DX 18-55 mm lens and a twin lightbox that provided uniform lighting of the piece. The images were shot in high resolution in JPG format for a basic reason, despite the fact that the creator of the *DStretch* plugin recommends using TIFF or RAW formats: as the first step consists of creating a photogrammetric model, we shot the images in JPG and then exported the high-resolution image to TIFF format using Adobe Photoshop.

Normally, it is recommended to save the shot in RAW format since it can be exported to TIFF, and both formats are a type of file with a larger amount of information that can later be modified with programs such as Adobe Camera RAW or Adobe Lightroom. However, when we decided to take pictures we chose to use the high resolution JPEG format, as it results in a smaller sized file than in RAW format, which makes the method more accessible to users who will often be forced to work with batteries of existing frames or graphics cards with less processing capacity. Although it is true that the processing time for the images in PhotoScan is the same when processing images in TIFF or JPEG format, for the purpose we proposed with this work, the use of the first image format was not a decisive factor. In fact, some professionals of archaeological photogrammetry have shown that the quality derived from the use of one or another image format in the photogrammetric processing only varies by a few microns (Aparicio, 2015), and so this is something that only needs to be considered when seeking millimetric precision. Finally, once the photogrammetric model has been obtained, the conversion of the final result to a TIFF format is due to the fact that its processing in other software such as *DStretch* is more fluid and practical.

There are two reasons for creating a photogrammetric model: the first is to obtain a high-quality image from a combination of a large number of frames, in which 70% of the previous images is overlapped, so that a very high definition is

obtained. This allows us to work in greater detail with areas in which the paint has been completely lost, or when the surface of the element has been severely altered by the presence of calcifications that cover the decoration. The second reason is to overcome the deformation caused by photographing a spherical vessel. The complexity involved in applying a tool such as *DStretch* to a complete ceramic vessel is that with one single image, many of the points on the pottery are hidden as it is a spherical vessel. It is important to note that the *DStretch* programme was designed for studying rock art paintings, which are mainly found in caves or rock shelters where the support is generally flat, as they are painted on the surface of the cave. For this reason, the result obtained from these types of studies is generally of excellent quality (Acevedo and Franco, 2012:154). Therefore, in order to overcome this problem and to obtain a vertical image that was as flat as possible, this step was designed as a part of the methodology described below.

As has already been noted by numerous authors (Luengo et al. 2018: 475), digital photogrammetry has now come of age. This passive documentation technique, based on the principle of structure from motion (SfM) offers a wide range of advantages and applications in the field of archaeological heritage. Photogrammetry applies the same principle as stereoscopic vision, that of human beings; in other words, it makes it possible to know the coordinates of an object by taking two photographs of it from different points of view (Charquero, 2016:180). The theoretical origins of photogrammetry date back to the beginning of the nineteenth century when it began to be applied to the development of aerial cartographies that were a good resource for military aviation. One of the main people behind its development was the Frenchman Aimé Laussedat, who made his engineering knowledge in creating topographic surveys available to the French army. Subsequently, Albrecht Meydenbauer used it to take images of emblematic buildings and monuments (Cheli, 2012: 15-16) in order to be able to safeguard a reliable copy in case they were destroyed. From that moment on, many scholars devoted themselves to the development of this technique, which reached a turning point in the 1990s when it became part of the digital era.

Today, the use of this technique has become widespread, allowing it to be applied in different disciplines, such as Archaeology. Although one of the main software programmes currently in use is Agisoft PhotoScan, there are previous examples that also marked a decisive moment in the development and consolidation of photogrammetry, such as *Photomodeler* and its later version *Photomodeler Scanner*

(Charquero, 2016: 140). A wide range of photogrammetric software is now available, such as *3DF Zephyr*, *ReCap Photo* or *Visual SFM*; however, *PhotoScan* was chosen due to its versatility and the wide diffusion it has within the field of archaeology.

This study case is included within what is known as close range photogrammetry. As previously noted, the main reason this documentation method was used was mainly based on the versatility of this tool, and the countless advantages it offers in terms of the options for visualising the object in question. As well as providing a good vertical view of the object, photogrammetry makes it possible to obtain a 3-D representation of the object, which unlike conventional photography, includes an optimisation of the cameras, and therefore a correction of the distortion that affects all camera lenses.

In order to create the 3-D model, *Agisoft PhotoScan* was used, a programme with very fast calculation speeds that is widely used in the archaeological research sector due to the simplicity of the different options it offers, the automation of the process, and the quality of the results obtained (Charquero, 2016: 141). However, when using a tool such as *PhotoScan* it is important to have a very clear idea of the intended result, in order to obtain the maximum quality.

In the case of the painted vessel from Portaceli, our aim was to record both the outside and the inside of the piece, without the need to combine both parts into a single model, as to do this, this study includes a 3-D reconstruction using more suitable tools than *PhotoScan* to obtain a better result, as described below. Therefore, only the process used to document the outside of the vessel is described, as the same steps were used in both cases.

The first step, and one of the most important in the photogrammetric process, was to capture the photographic image. The strategy used was to take photographs around the perimeter with an overlap of between 60-70% between the pairs of images (Fig. 3). This process was repeated at two other heights with a greater degree of slope, thereby obtaining overhead images that recorded the central part of the piece. Using this process, a total of between 120 and 130 photographs were obtained for each of the models.

Once the photographs had been taken, they were then processed using *PhotoScan*. The images were loaded and then masked in order to obtain a model with as little

noise as possible. The next step involved aligning the images (fig. 4), calculating the key points (the natural points that coincide in different images) and the tie points (the key points that coincide in different images). Following alignment, one of the most important steps to ensure obtaining good results was to apply a series of different filters that made it possible to automatically clean the point cloud. By applying these filters, it was possible to reduce the reprojection error of the images to a value of 0.87 pixels.

The next step consisted of creating the dense point cloud, which is when the depth maps are calculated. On this occasion an average quality was chosen in the image processing procedure, as high values are too large and slow down the process, and a moderate filtering mode. Once the dense cloud was obtained, the noise generated was cleaned up using the selection tools included in the programme. This made it possible to proceed with meshing the model (fig. 5). In this step, a random 3-D surface was selected, and the number of faces was customised in order to reconstruct the mesh in 0. By doing this, the programme creates a 3-D mesh from as many faces as are possible, depending on the original resolution of the images. On this occasion the interpolation was turned off, as it was not required to close the gaps resulting from the fragmentation of the ceramic element.

All that remained was to create the texture (fig. 6). As the aim was to obtain high-quality texturing, the generic mode for creating high-quality textures was chosen. This results in a more homogenous, uniform texture. A mosaic combination mode was used, with a texture size of 8192 x 1.

The final result was to obtain a high-quality, high-precision orthophotograph of both the inside and outside of the piece. This was the image used to apply the *DStretch* plugin, the main objective of the study. The aim was to discover the decorative design used on the piece, how it was created, and how well preserved the paint was.

The *Dstretch* plugin is an accessory of the *ImagenJ* computer programme, an open source image processing application, which can be downloaded free from <https://imagej.net/Welcome> for any operating system. The *DStretch* plugin was designed by Jon Harman<sup>2</sup> and can also be downloaded and used for free, which is the reason why the methodology described in this article is open to anyone

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<sup>2</sup> The *DStretch* plugin can be requested from its creator at not cost from the link <http://www.dstretch.com/>



interested in using it (Harman, 2005). *DStretch* processes multispectral images, altering the order of the RGB bands of the original image, and making it possible to obtain different results based on the selected working filter. By chromatically altering the images it is possible to create a false colour that highlights painted parts that are invisible to the human eye, either because they do not stand out from the colour of the support onto which the paint or decoration has been applied, or otherwise because this has been partially lost over time, or due to the post-depositional processes that affect archaeological remains, such as the presence of calcification.

The programme has a series of predetermined filters, which include YBR and LRE for reds, the colour that is most frequently used in rock art paintings, or YBK for yellows and blues. However, the programme has an Expert Mode, which contains all of the *DStretch* tools. In the case of this type of analysis, the most useful tool is probably *Hue Shift*, as it makes it possible to change the different degrees of saturation and colour in order to alter the contrast, and make the decorative motifs stand out. Nevertheless, each of the rock art paintings or elements has specific features, which means it is advisable to experiment with the different types of filters included in the application in order to obtain the best results.

Three filters were used with the vessel from Portaceli: two to study the outside of the piece, as this is the worst preserved part, and one for the inside. The exterior was analysed using the YRE filter (fig. 7) and YYE filter (fig. 8), altering their saturation values (Y, U, V) until obtaining the best result. For the interior, where the decorative motifs can be seen more clearly, only the YRE filter had to be applied (fig. 9), calibrating its values in order to obtain an excellent image of its decoration. By combining the three images, it was possible to make a new analysis of the decorative motifs on the post-firing painted vessel from Portaceli, which can be seen on the 3-D model shown below.

The final step in this methodology consisted of creating a 3-D reconstruction, with the aim of producing a complete piece that emulates the original design, thanks to the use of photogrammetry and *DStretch*. The goal was for the model to serve as a benchmark for studying the decoration on these delicate ceramic elements.

After analysing the data obtained from applying the filters to the original photographs, it became clear that one of the most important features of this type of linear, geometric decoration is the repetition of its elements, a facet that has been

previously explored by our group. The basic design is presented as a group within a quadrant of the piece, which is then repeated in the others by rotating it on its central axis. This means it was necessary to define a working strategy that focused on working with the decoration on one single quarter revolution, to then clone the design onto the rest of the piece by rotation.

The first step consisted of modelling the basic piece in 3-D. Although this vessel is hand-made, its perfectly symmetrical shape meant it could be treated as if it had been made on a potter's wheel. The process began with a geometrically simple model, creating a rotating surface generated from a documented section of the original piece. Splines were used to draw a section corresponding to half of the piece, and then rotating it on its Z-axis from the centre of the piece until generating a complete profile, with the uniform, circular geometry of a piece corresponding to luxury ceramic ware with hand-made shapes. This step was carried out using the open-source *Blender* software (fig. 10), a versatile programme that is accessible to any user.

Although Blender software was originally designed for use in the field of animation, in recent years it has become a fundamental tool for registration and representation in the field of Archaeology. This is because 3D tools make it possible to improve and optimize the method of archaeological documentation and recording, thereby making sites and objects more accessible to the general public (Kuzminsky and Gardiner, 2012). In the specific case of ceramic analyses, the subject of this article, more and more studies are addressing the usefulness of 3-D modelling for studying these types of objects, mainly because it represents a significant advance over traditional methods of drawing and representation (Martínez et al. 2010; Sánchez Climent and Cerdeño, 2014; Solórzano-Venegas et al. 2016) and is a very useful technique for scientific diffusion and publication.

The end result was a geometric shape that had to be subdivided with mesh smoothing, increasing the polygon density until achieving the optimum degree in the radial axis to correctly represent the circular shape around its parameter without exceed a specific number of polygons, as the aim is to work with a piece that can be consulted online from a viewing platform in the cloud. As a result, in this process it was necessary to optimise the mesh to prevent the smoothing from creating an excessive number of polygons in the opposite axis to the length of the section, with an excessive polygon density in zones that are unnecessary in order



to correctly reproduce the shape. To optimise the result it was necessary to add, remove, or move subdivisions in order to ensure that the inflections in the section and shape of the curve were reproduced correctly. In this stage it was also necessary to focus on the topology of the piece, checking the central part in the axis of revolution to convert the triangular faces that are generated by joining all of the subdivisions in a central point in four-sided polygons. From the different methods used to convert the central part into four-sided polygons, we chose the simplest in terms of optimisation, with a solution that ensures a good balance between the stretching that affects the central polygons as a result of subdividing a further step and the density of the resulting mesh, as this geometry should not be subdivided any more, unlike the cases where digital sculpting had to be used (fig. 11)

After modelling the piece and making sure that its shapes and cross-sections were correct, based on our reference piece, the geometry was prepared for the subsequent texturing process. To do this, only one quarter of the piece was used, in order to simplify the process, as the type of design made it possible to clone it from just one single quarter section.

The process of creating and organising the mapping coordinates (UVs) consisted of deploying the surface on which the texture was to be applied on a map, so that the layout of the polygons made it possible to apply a texture to them, in order to reproduce the physical appearance of the potter and its decoration, and to make sure that this is properly applied without any major deformities or overlaps. The correct deployment of the UVs made it possible to paint the piece both in a 3-D environment and to create the details of the decoration in 2-D, working with the texture on a map (fig. 12).

The technical complexity of this stage of the process lay in the fact that it was necessary to create a texture for the ceramic base that affected the whole piece, while the decoration was created for only one quarter of the piece, to avoid having to do four times the work. The combination of these two texturizing techniques meant that it was necessary to work alternatively on two different geometries –the whole piece, and one quarter of its circumference– which called for designing a working procedure with two different resolutions and two UV deployments in order to assemble the design of the decoration (1 quadrant) over the texture of the pottery (4 quadrants). By carefully planning this stage, it was possible to subsequently clone one quadrant onto the other three using coordinates to ensure

their correct positioning, and to avoid any discontinuity in the texture. It was decided to work at maximum resolution to guarantee the quality of the details, with the possibility of subsequently reducing this resolution if necessary; as a result, the resolution for each quadrant was 4096 pixels per side, and the total resolution of the quadrant would be twice the number of the pixels (fig. 13).

To create the texture of the vessel, it was decided to create it in 2-D so that it would be seamless, and could then be 'painted' onto the 3-D object. As the deployment of the UVs was organised in separate quadrants, and as there are always cuts in the deployment of a concave shape to prevent excessive deformation, the best way of applying the texture to the piece was by using the 3-D painting tool, so that it adapted to all of the outlines of the concave shape, and to prevent any discontinuities in the cuts for the four quarters of the piece (fig. 14).

The process was greatly simplified for the decoration, creating a series of reference lines on the 3-D piece in order to have an orientation of the distortions created by applying linear and geometric outlines to a concave or convex surface in the shape of a bowl. This reference was very important when it came to being able to paint the linear 2-D design more freely, then retouching as necessary in 3-D. The divergence between the subdivisions in the geometry (radial), the deployment of UVs with slightly curved shapes onto the map, and the linear and geometric illustration demonstrate the difficulty involved in applying this type of decoration onto a concave piece (fig. 15). To work with textures in 2-D, the open source *Krita* programme was used, an excellent alternative to Photoshop which makes this method accessible to different research groups.

The final stage consisted of creating the necessary textures in order to add a slight surface relief to the texture, and brightness or reflection to provide a slightly glossy veneer and enhance the surface texture. The model was then ready to export to *Sketchfab*, which was used to adjust the materials and lighting (fig.16).

<https://sketchfab.com/models/5b16d49cfeed41718e22aa7476746af6>

## 5. Discussion and results:

The decision to use the *DStretch* to study post-firing painted pottery came about as a result of the difficulty involved in handling these types of vessels. As they are decorated after firing, the paint does not adhere to the piece, which means the pigments deteriorate and are lost quickly, making the pieces difficult to handle.

Faced with the fragility of these archaeological pieces, it was necessary to develop a methodology that made it possible to study, handle, and preserve them. The aim was to discover the manufacturing technique used, and above all their decorative scheme, the most complex aspect involved when analysing these types of objects. The example of the painted pot from Portaceli is an ideal study case, as the piece was recently found in the collection of the Archaeological Museum of Badajoz in a fragmented, poorly preserved condition.

The only way of reconstructing the decorative motif on these types of objects is by observing the complete piece, as because they are geometric motifs they are very difficult to reproduce if the piece is highly fragmented. In this case, the poor state of preservation of the paint led to the design of a method that made it possible to observe the parts of the surface where the decoration was least visible. Thanks to the utility and excellent results obtained by applying the *DStretch* programme to documenting rock art paintings, and due to the similarities between the tones of the pigments used in both study cases (as red and yellow tones are the most widely used in post-firing painted pottery), it was proposed to use this image treatment tool on other supports, in this case a ceramic vessel.

In order to carry out the study, a methodology was designed that was divided into three stages. The first was aimed at photographing the object and creating high-quality orthophotographs, which would then be processed in *DStretch*.

Treatment of the image with *DStretch* was based on applying different filters or colour-spaces and other setting tools that make it possible to adjust the saturation and brightness of the original image, providing a clear image of the motif being analysed. In the case of the pot from Portaceli, the result obtained was not uniform, although the quality was excellent. Due to calcifications on the surface of the vessel and its partial deterioration, it was not possible to see the complete decoration; however, as this consisted of a pattern that is repeated in each of the quadrants of the design, it was possible to reconstruct the complete motif.

Therefore, the good results obtained from processing the image with *DStretch* were fundamental in modelling the piece in 3-D, mainly to complete its decorative pattern. The advantage of having a 3-D model of the vessel was that it was not necessary to manipulate the original piece. Also, if all of the decoration were lost, the model would make it possible to access the piece and have all of the information about its morphology (such as its measurements, paint colour, or

textures). Finally, this means that 3-D models can be printed that can be handled and studied, and allow for different restoration methods to be tested. As previously mentioned, one of the problems involved in restoring and consolidating the pigments found on these types of vessels is that the application of treatments alters the chemical composition of the paint, modifying any subsequent analyses of the pottery. Also, removing the calcifications found on these types of objects is not advisable, as the paint adheres to the limescale, and much of the decoration can be lost during the cleaning process. Therefore, 3-D printing vessels with similar textures makes it possible to test different restoration methods until arriving at the least invasive technique, something that opens the way for a new line of study and investigation. (fig. 17)

The methodology presented here must be applied during laboratory work. The estimated working time in this particular case was one week, which includes the restoration of the piece, taking the photographs, and applying the three methods described in this article. However, this time estimate is approximate, as it depends on the state of the piece to be studied and the computer support available to the user, which is fundamental for streamlining the process and making it faster.

## **6. Conclusions:**

Painted pottery is found along the entire Atlantic façade of the Iberian Peninsula, meaning the methodology presented in this study can be applied to a large number of case studies, many of which were recently analysed in a paper dedicated to defining this phenomenon from a chronological and technological perspective (Celestino, Rodríguez González and Donate, 2018). It may also be extrapolated to other types of painted pottery from different periods, while considering the fact that each piece has specific characteristics that make it different from the rest, meaning that the wide range of answers make each case different. The fact that the tool can be used for different applications does not mean that there is a closed protocol for its use, as it has become increasingly clear that although there are a number of common aspects to the study of all of the models, each piece or environment conditions the results, and so it will always be necessary to find the best variations depending on the type of object being analysed. Despite this, applying the methodology has proved to be very useful, especially in study cases where the archaeological remains are not in a good state of preservation. As a result, the study of the vessel from Portaceli has made it possible to identify its

decorative scheme, and to present a more accurate drawing and reconstruction of it, which differs significantly from the one that was published following its discovery. (Jiménez Ávila and Haba, 1995: 238, fig. 4).

Finally, the results obtained from processing the image obtained of the Portaceli pot with *DStretch* have shown how useful this tool can be when applied to other surfaces and types of archaeological materials, extending the previously limited spectrum of work carried out to analyse rock art paintings. *DStretch* has proved to be a versatile tool for preserving information that refers to archaeological heritage, with a simple, easy-to-use interface, and which is a free. It is also a non-invasive documentation method that is applied indirectly, making it an excellent complement to field work, and an exceptional contribution to the preservation and visualisation of different representations that will be available for future studies.

### **7. Acknowledgements:**

We would like to thank the Archaeological Museum of Badajoz, where the Portaceli vessel used in the study is currently on display. This study forms a part of the RDI Research Project of the Ministry of Economy, Industry, and Competitiveness of the Government of Spain (HAR2015-63788-P): *Construyendo Tarteso: análisis constructivo, espacial y territorial de un modelo arquitectónico en el valle medio del Guadiana*.

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### Figure captions:

Fig. 1. Photograph and illustration of the vessel from Portaceli (Medellín, Badajoz, Spain).

Fig. 2. First test runs for treating photographs using *DStretch* with images of the complete vessel.

Fig. 3. Scattered point cloud obtained after aligning the images. The screen shot shows the number of photos used to create the photogrammetric model.

Fig. 4. Dense point cloud

Fig. 5. Solid mesh

Fig. 6. Textured mesh

Fig. 7. External orthophotography treatment of the vessel with *DStretch*. YRE filter is applied.

Fig. 8. External orthophotography treatment of the vessel with *DStretch*. YYE filter is applied.



Fig. 9. Internal orthophotography treatment of the vessel with *DStretch*. YRE filter is applied.

Fig. 10. Development of 3-D modelling of the vessel using the *Blender* open-source software.

Fig. 11. Modelling work based on the polygons of the vessel.

Fig. 12. Deployment of UVs to start the texturing work.

Fig. 13. Design of the decoration in a single quadrant and cloning on the rest of the vessel based on the UV deployment.

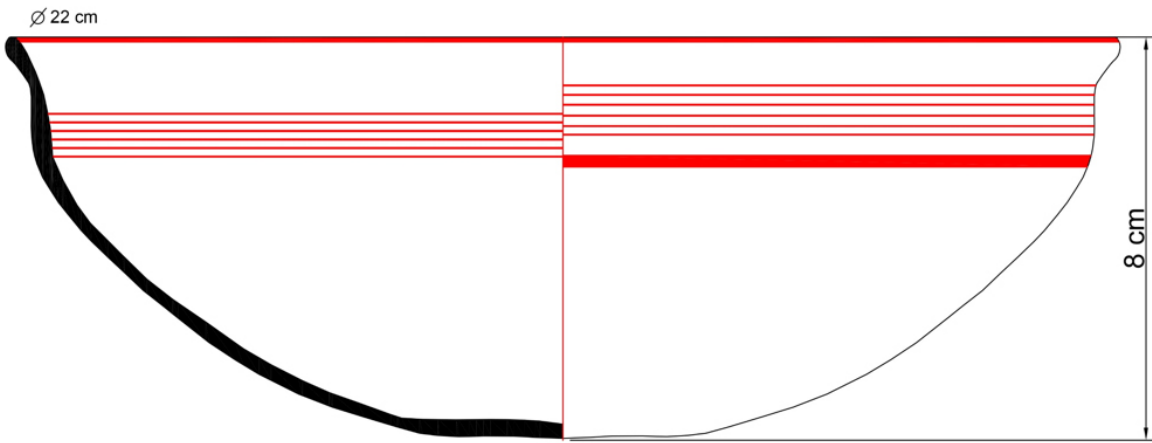
Fig. 14. Application of the texture using the 3-D painting tool.

Fig. 15. Design of the decoration and texture using the *Krita* open-source software.

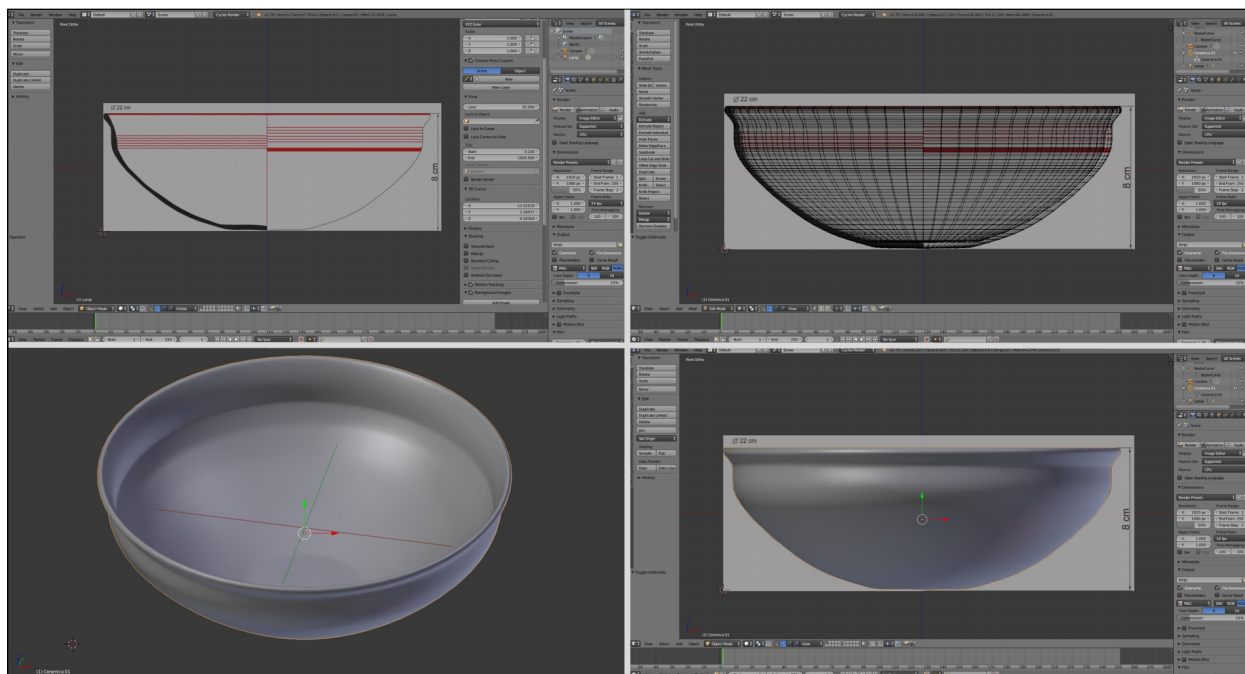
Fig. 16. Final result of the 3-D modelling of the vessel from Portaceli (Medellín, Badajoz, Spain) after texturizing.

Fig. 17. Schematic diagram illustrating the workflow

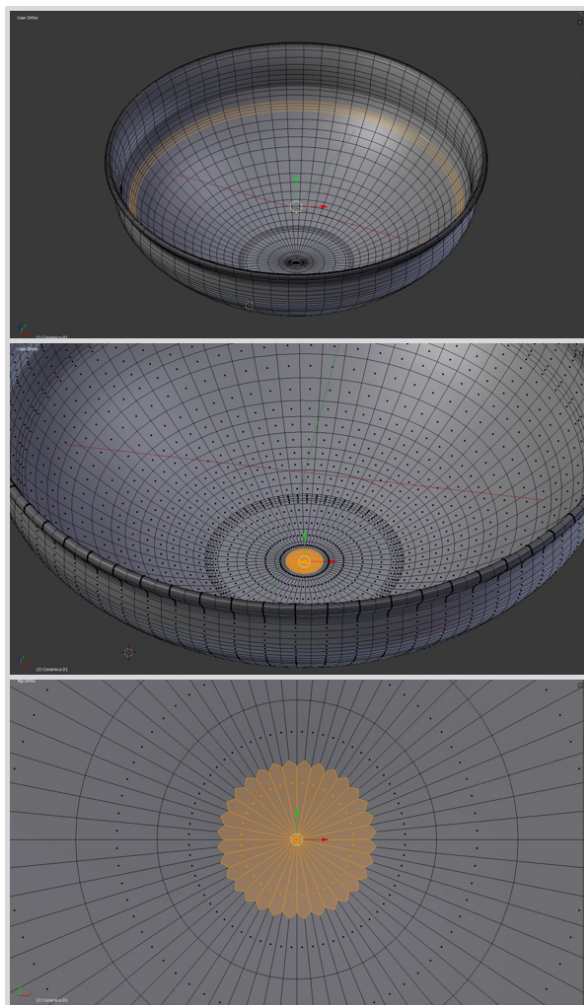




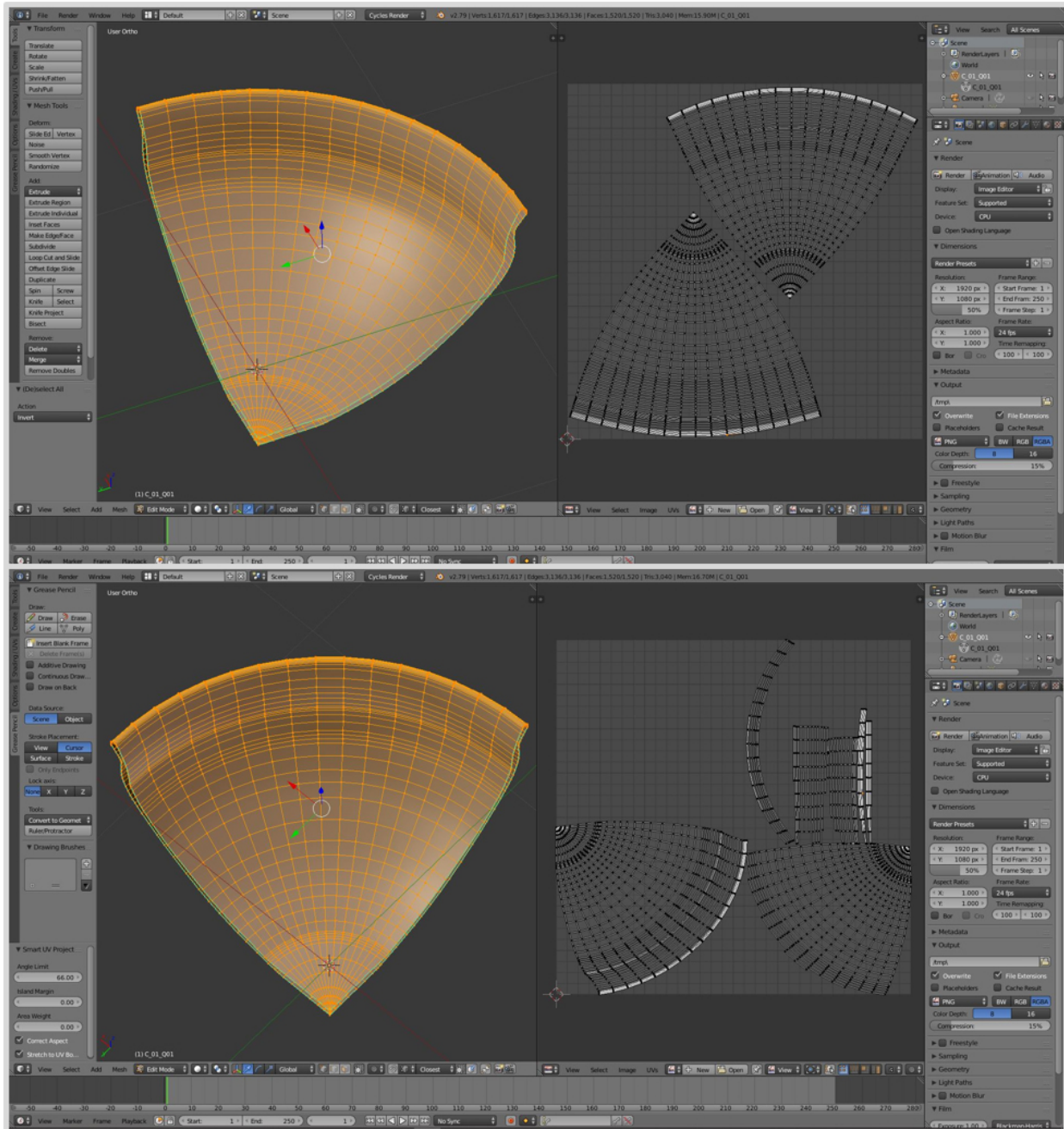
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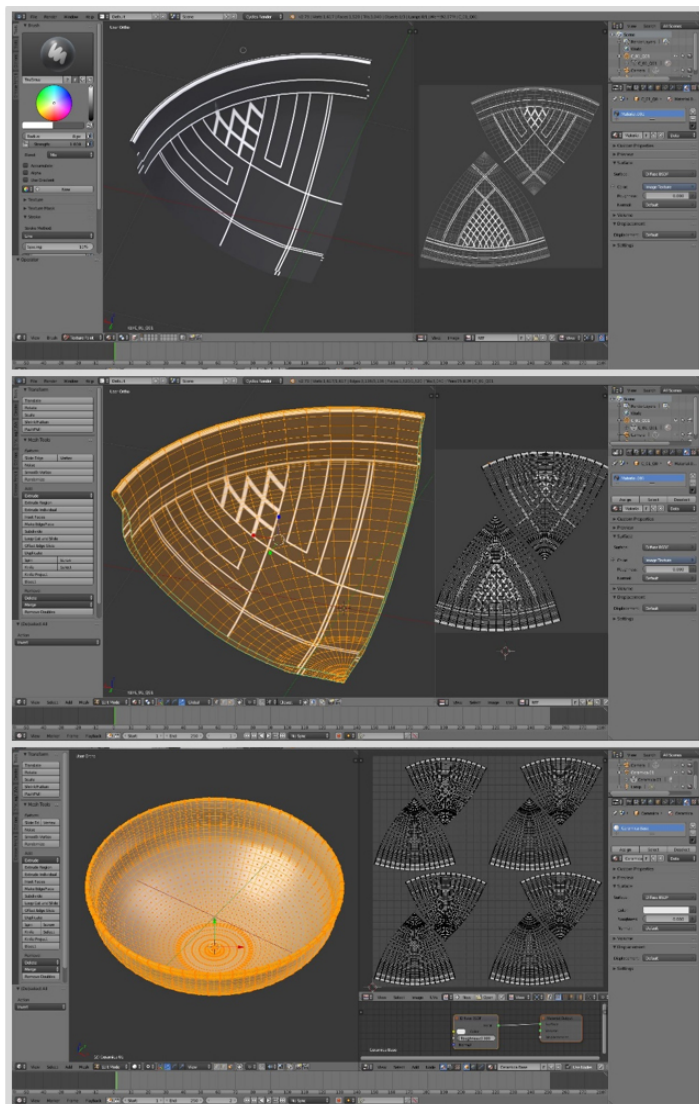


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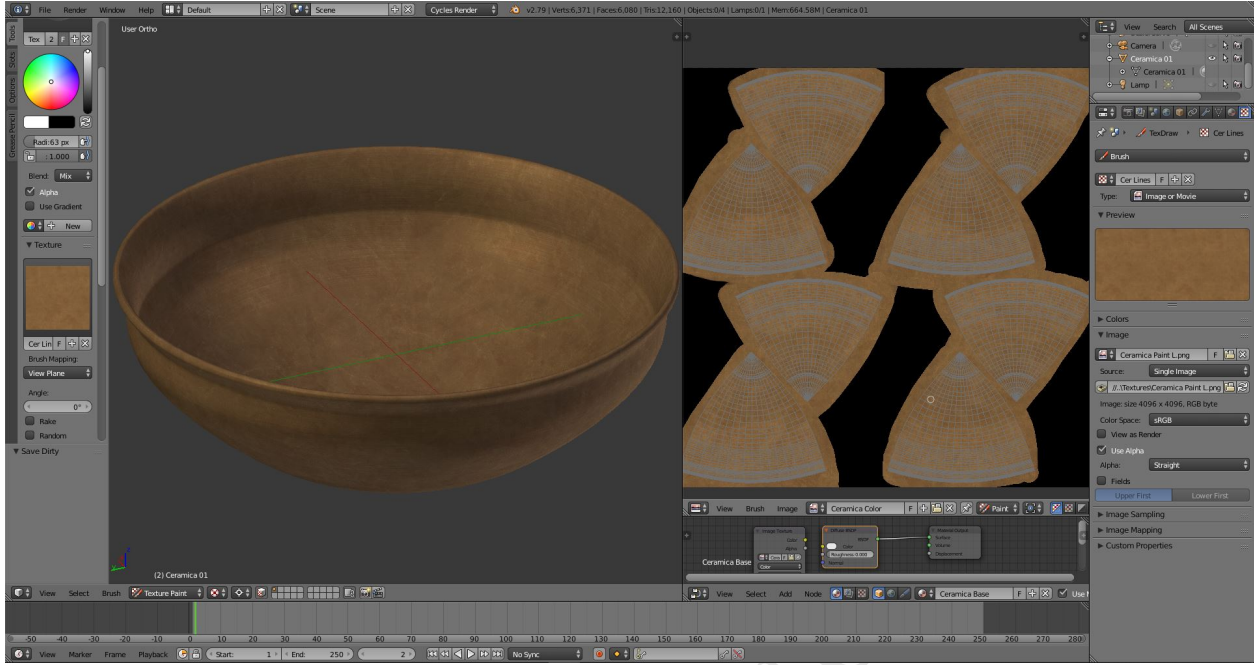




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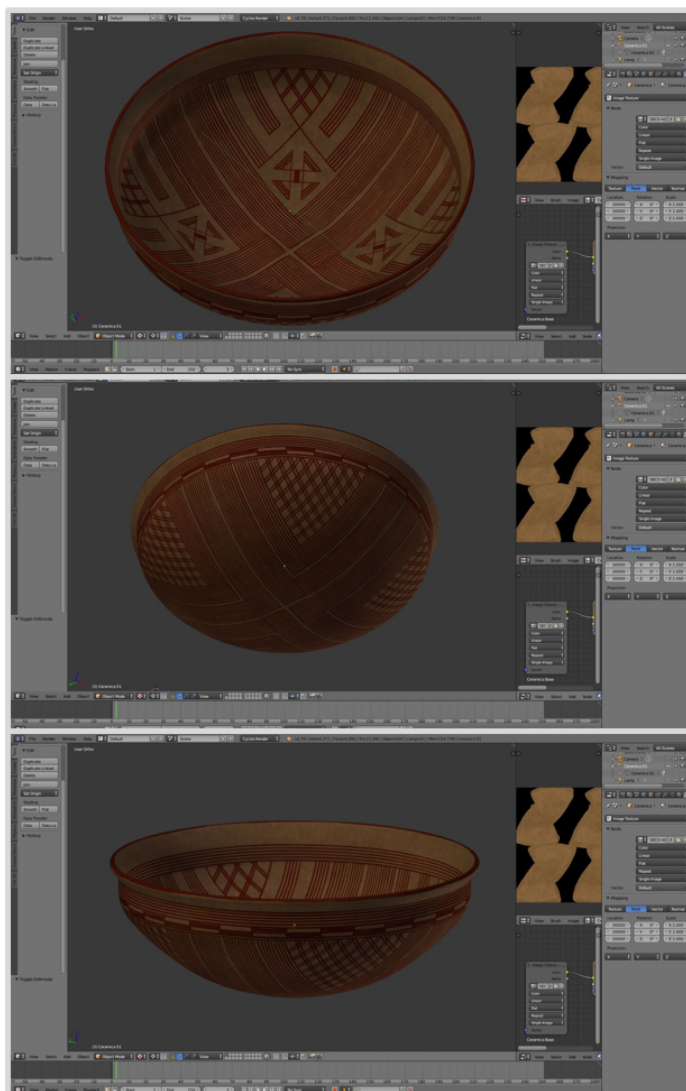




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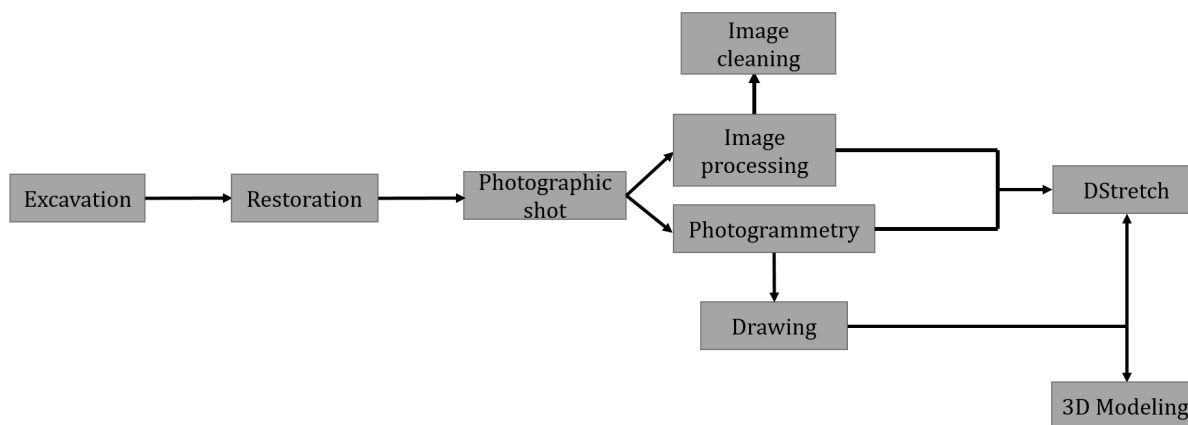
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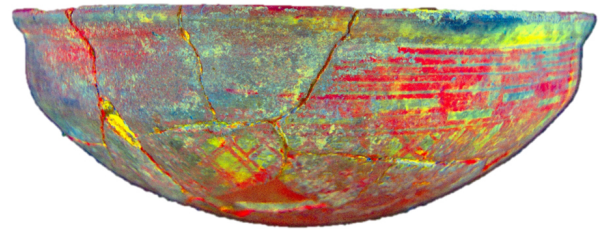
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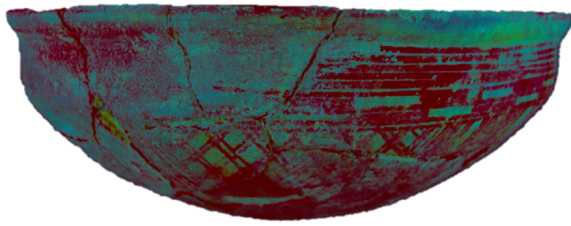




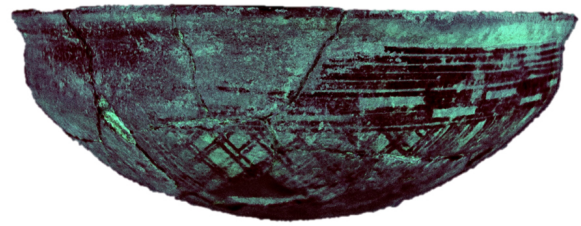
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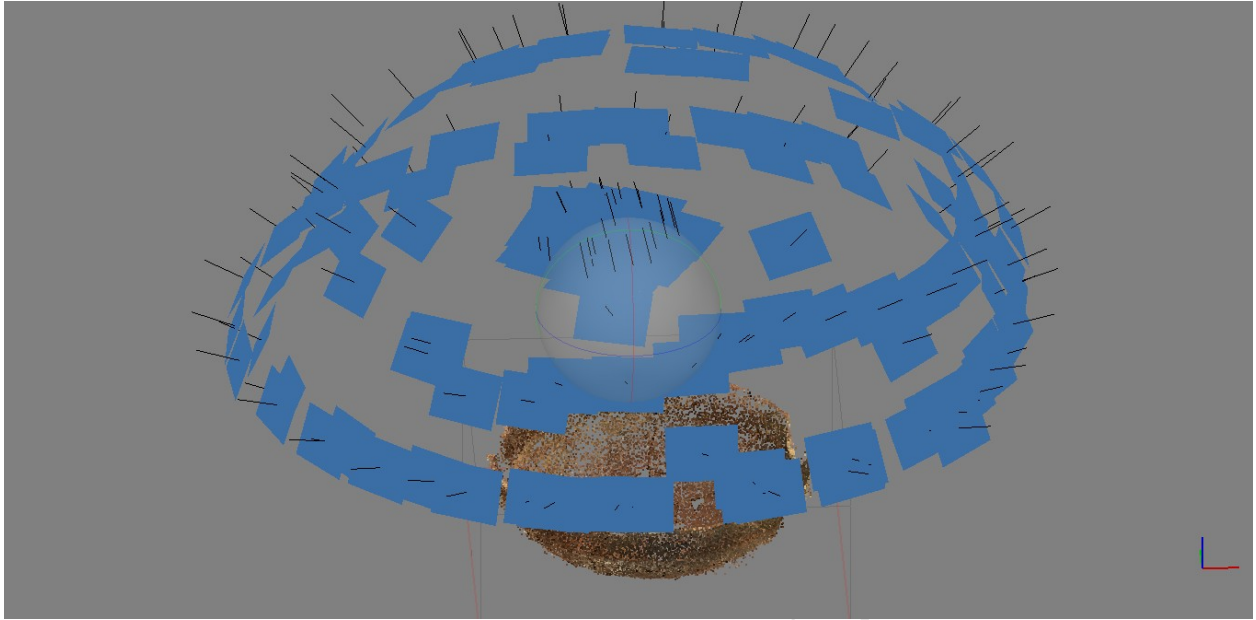


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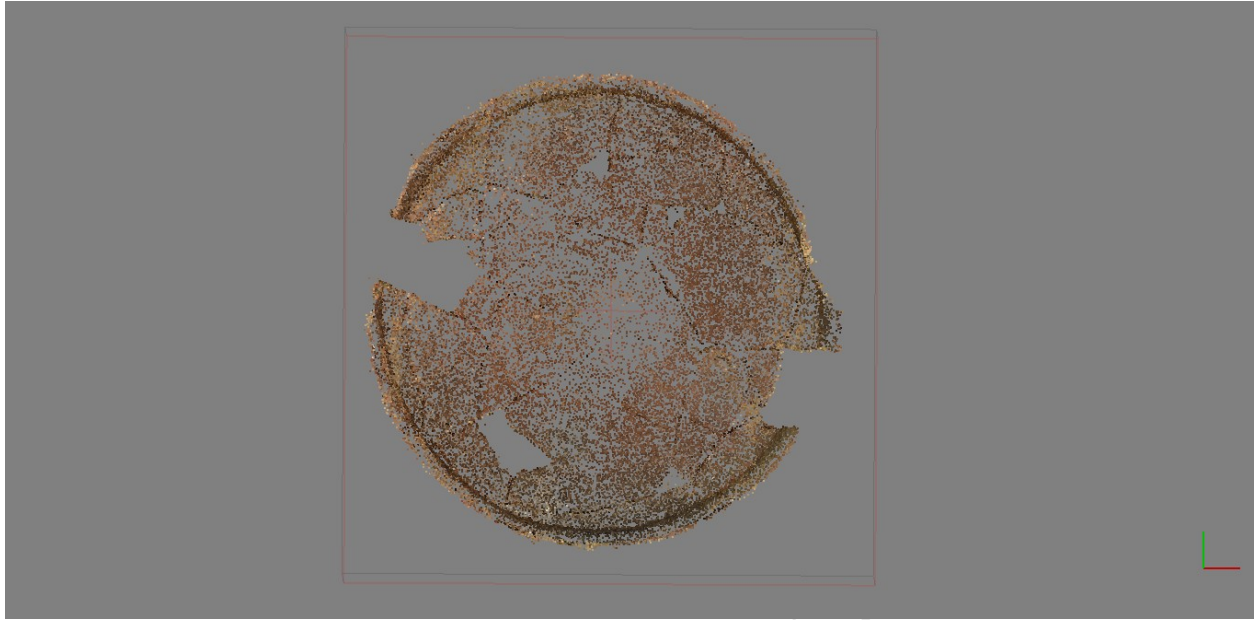


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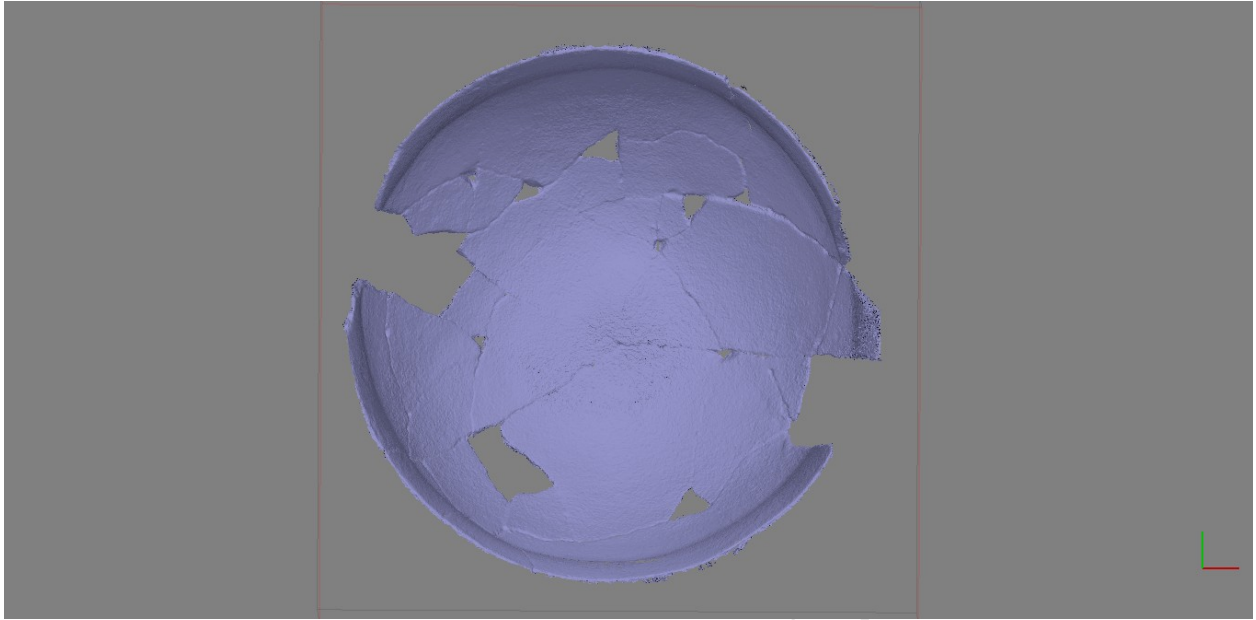
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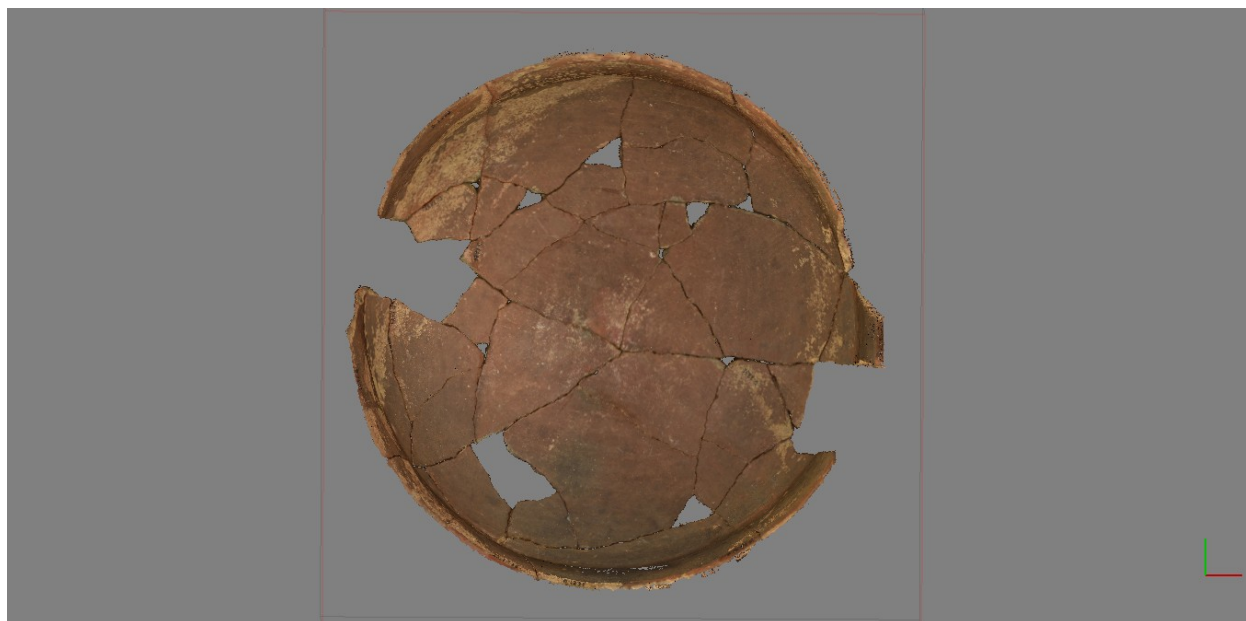
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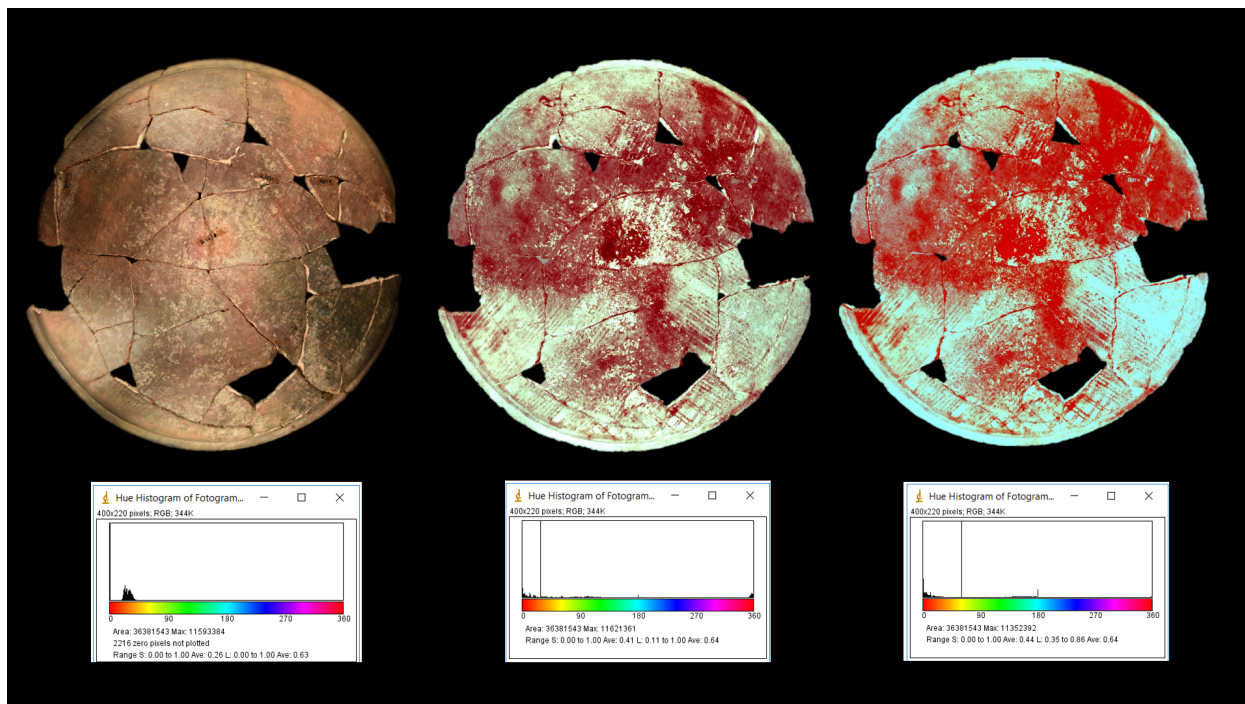
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