“3DMeshTracings”: a protocol for the digital recording of prehistoric art. Its application at Almendres cromlech (Évora, Portugal)

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Abstract: The recording of megalithic art on menhirs in Western Iberia used to be performed through direct tracing. The use of photographic techniques represented an important advance in the interpretation of some of the most important prehistoric sites in this wide region, and also in the structuring of archaeological narratives. With the development of photogrammetry, the possibilities have improved considerably, enabling the recording of decorations not visible to the naked eye. In this paper, we present a new protocol to highlight the engravings on eroded surfaces, based on High Performance Computing and advanced algorithms for 3D mesh calculation. This tailored protocol has rendered expressive visual results that have succeeded in recording one of the most exceptional cromlechs in Western Europe: Almendres (Portugal). The results have proved the efficiency of the method and the need to revisit the classic megalithic sites.

- A method for speeding up the recording of megalithic art in complex sites is presented.
- The application of the methodology has been able to discover both unpublished motifs and stelae at one of the most relevant sites in prehistoric Portugal (Almendres cromlech).
- The new interpretation has served to obtain evidence about several phases of decoration, suggesting a diachronic reworking of the pieces that compose the cromlech
- The new discoveries allow connections to be traced between the Iberian Peninsula, Brittany and Southern France during Late Prehistory

1. Introduction

The study of European post-glacial art is grounded on the decoration of megalithic monuments to assess questions about their functionality, chronology and phases of use. The fact that stelae, menhirs and monuments located in the open-air can be included in this group of expressions is fully admitted by European historiography, and therefore menhirs can be included in the wide context of Megalithic Art (Bailloud et al., 1995; Benéteau-Douillard, 2012; Bueno-Ramírez et al., 2016, 2007; Calado, 2002; Migdley, 2013). In Europe, a menhir is defined as a standing stone artificially raised. Its surface might be prepared and decorated with both engravings and paintings. In the Iberian Peninsula decorated standing stones with a round cross-section are classed as menhirs, whilst those with a single flat side decorated with anthropomorphic engravings are traditionally regarded as “stelae-menhirs”. Some authors (Ferraz, 2016; Gomes, 1994) have interpreted these differences in terms of chronology. Menhirs would be the most ancient and would be transformed later into menhir-statues. However, this hypothesis was established as a fact and grounded on a methodology that incites highly subjective interpretations. The recording of their decoration has been accomplished using diverse methods, from the inappropriate direct tracings (Gomes, 1994) through the generalized use of conventional photography and photogrammetry (Bueno-Ramírez et al., 2014; Carrero-Pazos et al., 2016; Cerrillo-Cuenca et al., 2014; Domingo et al., 2013).

The digital recording of rock art has today both a reasonably long history and a brilliant future. Since the early 2000s several papers have described research methods to trace paintings and carvings (Cerrillo-Cuenca and Sepúlveda, 2015; Chandler et al., 2007; Clogg et al., 2000; Lerma et al., 2010). Most of these have stressed how digital methods can reveal hidden aspects of the decoration of rock carvings (Alexander et al., 2015; see Cai, 2011 for a broad discussion) or paintings. A generalised and mainly shared conclusion is that digital methods can enhance significantly what can be perceived only by the naked eye. The future of such methods seems to be bright since computer vision is an area that is exponentially growing with new interesting features (Szeliski, 2010) that can be applied to rock art recording.

The aim of this paper is twofold. First, we describe a new method for recording the rock art of complex monuments by advanced digital techniques that comprises a certain number of solutions, from the field recording to the processing of information. To accomplish this goal, we have designed a whole workflow (Figure 1) that covers from the recording in the field to the production of interpretable digital images. As in many other current archaeological projects, the core technique is digital photogrammetry, or more specifically Structure from Motion (SfM). The benefits of using digital SfM in the recording of prehistoric art have been stated elsewhere (Alexander et al., 2015; Cai, 2011; Carrero-Pazos et al., 2016; Carrero-Pazos et al., 2018; Cerrillo-Cuenca et al., 2014; Plets et al., 2012); the most recurrent of them is avoiding direct contact with the decorated surface. SfM is nowadays an affordable technique that provides immediate results with acceptable accuracy, which can explain the rapid spread of the technique among archaeologists.

To illustrate the method, we have chosen one of the best-known megalithic sites in Western Europe: Almendres (Évora, Portugal). A specific key question is if the use of digital technologies can alter significantly the archaeological knowledge that has been

produced through a visual or, in the best of the cases, a photographic interpretation of decorated pieces at classic megalithic sites. Our work also intends to record engravings at complex sites by designing an efficient and affordable workflow. By complex site we mean an archaeological site composed of several elements or pieces (menhirs, slabs, etc.) with different structural complexities, that considerably exceed the reduced number of pieces that other studies have analysed through digital technologies (Cassen et al. 2014; Plets et al., 2012 and many other study cases). It can be problematic to determine whether the recording of a site is “complex” or not, but we can consider that the processing of over 15-20 pieces can be a challenge under normal circumstances, considering the time that should be invested in processing and analysing the digital information, and especially the time that photogrammetric restitution takes. Sites like Almendres, formed by nearly a hundred pieces, require more developed techniques to facilitate the recording but also to process the great amount of digital information that each site produces. Thus, one important point of the methods described here is that they make use of High Performance Computing (HPC) to speed up the photogrammetric processing of image sets.

The application of HPC techniques in prehistoric art recording can be seen as a novelty. As we will describe and discuss below, for this study we utilised a cluster of processors and Graphics Processing Unit (GPUs) to parallelise calculations. Finally, an additional strength of our workflow is that the numerical processing of digital information along its different stages has been applied out automatically, thanks to a tailored own code that uses several open source libraries.

2. Methods

We have named this protocol “3DMeshTracings”, since it aims to produce volumetric information of megalithic supports through the application of mathematic procedures to 3D photogrammetric meshes. It is essential to account for volumetric representation in megalithic art recording, since many of the decorated supports in graves or open-air sites (cromlechs, isolated menhirs, etc.) were conceived as decorated volumes or as architectural parts. Thus, in this specific case the analysis of decorated supports in a 3D environment overcomes the conventional needs for representation and finds a field of development in current digital technologies. 3DMeshTracings aims to combine the current methods and know-how for recording megalithic art with an *ad hoc* digital methodology intended to catalogue and interpret megalithic sites. Our goal is to present a consistent and reproducible procedure, for which we describe in detail the whole process and the used algorithms. In short, the protocol described in this paper consists of three stages: 1) the recording of pieces in the field (Figure 1: Steps 1-2), 2) the photogrammetric processing of photographs (Figure 1: Steps 3-4) and 3) the digital enhancement of engravings through mathematical procedures (Steps 5 to 8). Figure 1 summarizes the protocol.

2.1. Labelling pieces in the field: automatic QR codes

Recording complex sites requires a full strategy to label every single element that will be later processed. To automatize the organization of images for later photogrammetric processing, a Telegram bot was written in Python programming language. Telegram is a popular client-side open source messaging app for smartphones and computers that can create interactive chats (bots) to interact automatically with the user in real time. In our case, a simple bot was programmed thanks to Telegram Bot API

[<https://core.telegram.org/bots/api>] to process basic information delivered by the archaeologist in the field (coordinates, site and number of pieces) and return a picture in a few seconds with a QR code containing all the information. QR codes have been widely used in archaeological projects (Forssman et al., 2016). In this case, we seek to automatize the uploading of information to the HPC facility by labelling each set of photographs with the information contained in QR codes. Thus, we took a photograph of the smartphone screen displaying the instantly generated QR code before recording with the same camera a new piece. A second script read the QR code in the image and organized the whole set of images in individual folders for each piece, which was automatically uploaded to the HPC facility.

2.2. Photogrammetric restitution

Different SfM software with diverse capabilities and functionalities are at the disposal of researchers. However, not all of them can be parallelised in an HPC environment. Colmap is open source software that implements powerful features to develop all the steps of a standard digital photogrammetric restitution, from image matching to mesh production covering all the intermediate steps. Moreover, scientific information about the algorithms has been properly published (Schönberger et al., 2016; Schonberger and Frahm, 2016). Preliminary tests show that this software is able to produce very detailed and precise 3D products such as point clouds or meshes thanks to a revision of the SfM technique (Schonberger and Frahm, 2016). Colmap was compiled in the HPC facility using Compute Unified Device Architecture (CUDA) libraries to use the available GPUs (Nickolls et al., 2008) at the HPC cluster. The strategy consisted of processing a piece per each available node from the cluster, which was always equipped with two high-end GPUs for scientific calculation. However, not all the binaries from Colmap software were designed to parallelise tasks in a GPU environment, therefore only image matching and dense reconstruction, which by the way are the most time-consuming tasks, were set to work in GPUs.

The result (Figure 2) was a point cloud composed of between 3.5 and 9.5 million points depending on the size and formal complexity of the pieces examined in the present study case. This point cloud contains geometric information and also the orientation of individual points (normals) and the colour values (RGB) derived from the image sets.

2.3. Cleaning of point clouds

Once the point cloud was generated (Figure 2), an *ad hoc* code written in C++ programming language performed an automatic cleaning of the point cloud. Part of the code was written by linking instructions from Point Cloud Libraries (PCL) (Rusu and Cousins, 2011) and The Visualization and Computer Graphics Library (VCG), made available by the Italian National Research Council Institute. The code uses different libraries to segment the geometric information and removing the outliers, isolated points whose coordinates were two times the standard deviation of the local surface. Finally, the point clouds were segmented considering Euclidean distances. Through this step, we suppressed all the background information (vegetation, other pieces, etc.) from the point cloud (Figure 2). This process can be very appropriate when recording sites like Almendres, formed by isolated menhirs, but can present problems when dealing with other kinds of monuments. In this case a visual inspection of the obtained point cloud is recommended before proceeding with the next step.

2.4. Mesh triangulation

To obtain a neat product for interpreting distances it becomes necessary to convert the geometry of point clouds into a 3D mesh. A 3D mesh is a set of vertices, edges and faces that are connected together in a 3D space forming an organised data structure (Gortler, 2012, p. 226). A mesh can be obtained through the interpolation of dense point clouds with normals. An affordable technique is Poisson Screened Reconstruction (Kazhdan and Hoppe, 2013), which is implemented in several software packages. In our case, we built an executable from the original source files. For all the cases, the value for the depth reconstruction was set to 13, in order to adapt the mesh to the tiniest details of the rock surface in the newly created mesh. Figure 3 shows that depths below 12 produce undetailed meshes, so a depth of 13 seems to be a balanced value between the quality of representation, accuracy and processing. Additionally, we processed two additional meshes at a lower depth resolution to compute Hausdorff distances, as we explain below.

2.5. Hausdorff distances

The numerical comparison between high resolution and smoothed surfaces is a useful technique for revealing height differences (Figure 4). This technique has been often applied in the archaeological analysis of LiDAR datasets, for instance in the so-called Local Relief Model (Hesse, 2010). In the case of meshes representing volumes or surfaces, Pires et al. (2014) or Cassen et al. (2014) have designed similar approaches based on the comparison between an original high-resolution mesh and its transformation through decimation or smoothing. “Morphological Residual Model” (Pires et al. 2014) or “Deviation Map” (Cassen et al. 2014) procedures have shown success in revealing engravings in different surfaces, however neither the mathematic rationale behind the process nor the parameters for interpolating the meshes have been explicated, which would have enabled us to compare the differences with our methods in a more suitable form.

In our case, we made use of Hausdorff distance to estimate the distance between the surfaces of two 3D meshes. The mathematical rationale underlying the Hausdorff distance has been published elsewhere (Aspert et al., 2002, p. 705; Cignoni et al 1998, p., 168; Rockafellar and Wets, 2009, p. 118; Taha and Hanbury 2015). The Hausdorff distance between two sets of points can be estimated by the formula (Taha and Hanbury 2015, 2153):

$$\partial H(A,B) = \max_{x \in A} \{ \min_{y \in B} \{ \partial(x,y) \} \}$$

Where δH denotes the Euclidean distance between A and B sets of points. δH is the maximum of distances between each point $x \in A$ to its nearest neighbour $x \in B$ by using the Euclidean distance function. This procedure has been recurrently used in computer vision to evaluate the “closeness” between two sets of points in a Euclidean space, and can be applied to estimate the differences between two meshes, for example an original one and its simplification (Cignoni et al. 1998). The calculation of Hausdorff distance can be used to reveal local differences between two 3D meshes and to assess their quality by considering the position of their vertices regarding a surface (Aspert et al., 2002). The Hausdorff distance is not two-sided (Cignoni et al. 1998: p. 168), that is:

$$\partial H(A,B) \neq \partial H(B,A)$$

Thus, we have used the vertices of an A regular mesh (interpolated at a depth of 13) as the compared mesh (Figure 4a) and the surface of a B simplified mesh (interpolated at lower resolution) as the reference (Figure 4b). VCG implements the Metro tool (Cignoni et al. 1998) for estimating the Hausdorff distance, and it is also available in the Rvcg and Morpho packages for R (Schlager 2017). The results are vertices representing the one-sided Euclidean signed distances (positive and negative) from B to A. The carvings are then highlighted (Figure 4c), and can be transformed into a more convenient grayscale for a proper interpretation.

We also designed a procedure to maintain the finest traces of engravings and the most evident ones. Three meshes were interpolated through Poisson Screened Reconstruction from the same point cloud at different depths of 6 (Mesh A), 10 (Mesh B) and 13 (Mesh C) (Figure 5). By comparing Mesh C to Mesh A through Hausdorff distances we can reveal the roughest and wide engravings, whilst by comparing Meshes C and B we obtain the thinnest ones. Then, the two obtained grayscale results were fused into one and mapped on Mesh C (Figure 5) by averaging the gray values of the vertices.

2.6. Visualization

Adjusting the parameters for visualization is an important key to detect the engravings. We used CloudCompare, an open-source point-clouds editing software, that offers a vast range of tools to visualize and edit meshes, and ParaView, that allows efficient treatment of visualization through several parameters. The vertex-coloured meshes derived from the calculation of Hausdorff distances were imported into CloudCompare and fused. Once their histograms had been consulted, the visualization scale was adapted to stretch the visualization to the minimum and maximum values of the histogram. Grayscale has been the most adequate colour scale for revealing engraving, as this colour scale is quite similar to the procedure used in conventional archaeological illustration. After the meshes were treated and oriented in a normative representation they were exported as regular image files. These images and meshes were used for interpreting the decorations of the pieces described in section 3.

2.7. Tracings

The obtained images are expressive enough for interpreting the decoration of the pieces. Tracings can be considered as an ancillary representation of the protocol and can be obtained through the manual vectorization of images. A further more complex system can involve the segmentation of colour scales considering the signed Euclidean distances between two meshes (see section 2.4). This approach can serve to assess the different types and widths of engravings, being especially important in the case of Almendres, where bas-reliefs and carvings are combined. Therefore, we can obtain and represent detailed information about the engravings in a particular position of the piece by segmenting positive and negative intervals of Hausdorff distances. A similar procedure has been proposed by Cassen et al. (2014, 131). Additionally, we can quantify and assess the depth of the engravings considering the numeric values rendered by the Hausdorff distance algorithm. Figure 6 shows a possible outcome for this process.

3. The study case: Almendres (Évora, Portugal)

Decorations on the menhirs in Central Portugal have been revised during the last decades in a broader sense (Ferraz, 2009). Cromlechs like Almendres (Alvim, 2004; Gomes, 1994), Portela de Mogos (Gomes, 1997a) or Vale Maria do Meio (Calado, 2000, 1997) initiated a fruitful field of research, which has continued in recent years (Alvim, 2013, 2009; Bueno-Ramírez et al., 2015a; Calado, 2004; Gomes, 2011; Rocha, 2016).

Almendres is one of the best-preserved prehistoric cromlechs in Western Europe and is formed by 95 menhirs (Figures 7, 8 and 9). The site was discovered by Henrique Leonor Pina (1976, 1971) during the 1960s and excavated later by M. V. Gomes (1997a), who also published the decoration of some menhirs and stelae (Gomes, 1994) and undertook a new documentation of the menhirs. Calado (2002) studied the site in a wider work that considered other proximate sites; cromlechs as well as isolated menhirs. Our study of the site concluded that most of these menhirs could have been erected during the sixth millennium cal BC. Finally, P. Alvim (2009, 2004) conducted a new project on the site. Alvim (2013) also made a photogrammetric survey of some menhirs that has been partially published. However, this new photogrammetric documentation did not apparently offer new results about the engraved menhirs. Ferraz (2016) developed a new survey based on nocturnal photographs that revealed some novelties. As a matter of fact, the comparison between the noticeable results of the latter study and ours shows the efficacy of the system here described.

Almendres menhirs were executed in diverse granite rocks. Whilst other cromlechs in the Alentejo region, like Portela de Mogos (Cardoso et al., 2000), have been analysed petrologically, this kind of analysis has not been conducted at Almendres. Mineral grains of different qualities and sizes show that the source of raw materials should be fairly diverse, which might have influenced the preservation of engravings. The weathering of granite surfaces is another factor to be taken into account since several menhirs present intense weathering patterns that might have affected the preservation of engravings and also possibly of paintings. The discussion of such aspects goes beyond the aim of this paper; however, the proposed protocol should account for different degrees of preservation.

4. Results and discussion

4.1. Performance of the field recording and computing processing

Thanks to the implementation of QR codes, tens of pieces can be photographed in a day and automatically organized in minutes with a little supervision. Although this part or the whole 3D Mesh Tracings workflow can be more or less irrelevant, it copes extraordinarily well with one of the aims of the protocol: to ease the recording of megalithic sites.

More than 12,000 photographs were taken during the recording of the Almendres menhirs. An average of 135 images per piece was obtained, where the maximum number of photographs per piece was 305 and the minimum 35. Regarding the taking of photographs, it must be noticed that it was not always possible to shoot with a shadowless light. However, this circumstance seems to have no effect on the creation of 3D point clouds. Gathering all the information contained in the headers of photographs, the documentation of the site was accomplished in 4 hours and a half (4:35:36h). The whole

documentation was carried out by a single person during 4 non-consecutive days. Those are real improvements compared with other reliable methods that are more time-consuming (Díaz-Guardamino and Wheatley, 2013).

However, it is not easy to determine the time that the processing of data at the HPC took. The difference between the available CPUs and GPUs models in the several nodes of the cluster made it impossible to determine the time that it took to process all the information. Moreover, the disposal of free nodes was unequal during the processing of the dataset, which hinders establishing the real time that the whole processing took. An average of 3 hours per piece seems to be a reasonable estimation, so the whole site could have been processed in about 280 hours of computation. With an availability of 10 simultaneous working nodes, all the photogrammetric and mesh processing tasks might be completed in approximately one single day.

Regarding the outputs of dense reconstruction, a total of approximately 565 million points was generated, of which 331 million were employed to generate meshes. The individual and yet cleaned point clouds contain between 10 and 0.5 million points, values which are strongly dependent on the size and complexity of each individual piece. The average number of individual observations in point clouds is 3.5 million per piece. All these values are increased if we consider the number of generated vertices after performing the Poisson Screened Reconstruction, approximately more than two times the number of points from a dense point cloud. The achieved resolution has proved to be high enough for recording the already known engravings, but also a significant number of new, and mostly subtler, engravings that were not recorded during previous survey works.

4.2. A brief appraisal of results: three study cases

Three representative menhirs at Almendres cromlech were selected to illustrate the present study: menhirs 31, 62 and 64 after the numeration of Gomes (1997). All of them are located in the area of the site with less decorated pieces. In every case new engravings and motifs were detected, improving our knowledge of the decoration of Almendres cromlech and its phases. These three cases can be seen as an advance to an ongoing complete analysis of the site. The basic descriptors of their photogrammetric restitution can be consulted in Table 1.

4.2.1. Case 1. Menhir 62: identifying new engravings on highly eroded surfaces

Menhir 62 (Figure 10) stands near the middle part of the cromlech (Figure 9). Following Alvim (2013) this piece was found fallen after the discovery of the cromlech and re-erected later during restoration works. This piece was not identified as decorated until recent studies (Ferraz 2016) because no motifs are visible to the naked eye and daylight illumination, and the engravings published by that author have been enriched by the revision discussed here. The cross-section of this menhir is almost square. The frontal side, which contains most depictions, was worked to render an oval shape where an anthropomorphic representation was sculpted. The technique involved engraving as well as bas-relief, which is frequent in other pieces at Almendres.

The apical zone has been crafted in the same manner as the classic “eyed” idols in megalithic reliefs, of which the best-known is Stela I21 in Soto Dolmen (Bueno-Ramírez et al., 2018). This formula represents the nose included in an upper arch formed by the

eyes, and thus the “T-shaped faces” are named after this kind of depiction. The vertical undulated engravings next to both sides of the face are indicating the clothing of the personage, as commonly occurs in other megalithic contexts. An elongated triangular piece, slightly thickened in its upper part, hangs from the necklace; this is the first known Iberian case where objects hang from a band close to the neck (Figure 11a). This depiction resembles more well better-known examples in French menhir-statues. We are referring to *l’object*, which is interpreted as a not necessarily metallic sheathed dagger (Maillé, 2010, p. 129). On the proximal side, a “crook” was carved in bas-relief, forming one of the few sequences of objects known in these pieces. It should be stressed that the block was originally shaped to obtain a sculpturesque finish. The sculpture “stands out” from the stone (Bueno-Ramírez et al., 2008).

The reverse displays a single engraved “toroid”. The examination of the sides has also revealed new motifs, hardly visible in the field, since the surface of the rock presents natural cracks and quartz bands that hinder the recognition of engravings.

It seems that the old surface on the reverse side was reworked and at least two “crooks” were engraved on the new surface, one next to the other in the middle part (Figure 11b). Below, on the original preserved surface, an oblique double-line is appreciated. By considering its position, we can suggest that it might have originally been longer. A line that could correspond to a belt can be identified higher up. Hence, this stela was sculpted over a reused piece that was taller originally. Part of its decoration was removed, as the strong reworking of the reverse suggests and later, once the “T-shaped face” stela was sculpted, a crook was added over its necklace with a dagger.

4.2.2. Case 2. Menhir 64: revisiting a classic piece

Menhir 64 (Figure 12) is one of the classic menhirs at Almendres. Its engravings are clearly visible to the naked eye, mostly because the original engravings have been brushed up by visitors in recent times. Gomes (1994) published the first tracing of this piece, and this has been followed by most recent authors. Ferraz (2016) proposed a new reading of the piece that is more accurate in some points, although it does not account for several motifs presented here.

The decoration of this menhir was developed on the two widest sides of a conical support. The surface of the piece is uneven, and several natural cupmarks can be distinguished. The obverse faced towards the East, in a parallel position to a piece decorated with circles and rays (number 52), which might be eventually interesting to propose probable meanings. Both pieces present circular motifs with abundant links to both schematic and megalithic art in the Iberian Peninsula. Menhir 64 was described as displaying two circular motifs associated with vertical lines and a circle, resembling “flasks”. Our documentation reveals a first phase of plain circles and below them concentric ones, especially condensed on the lower part of the piece, indicating a possible continuation of the motifs below the ground. The so-called “flasks” connect with older circles, which possibly denote a way to connect circles from one phase to those from a previous phase. The three most prominent circles have been cleaned up and marked with chalk, making them more visible. On the left of the reverse, the triangular face of an axe can be appreciated, carved with very superficial pecking. The circles from the first of the phases are abundant on the other sides, suggesting that only the obverse was carved during the last phase (Figure 13a); that is, only the side facing towards Menhir 52. On the reverse, a

rectangular shape occupies the entire surface, finishing in an apex in the upper part (Figure 13b). This is a shape that evokes some well-known megalithic stelae at other Iberian and Armorican sites (Bueno-Ramírez et al., 2018) (Figure 14).

4.2.3. Case 3. Menhir 31: an unpublished piece

Menhir 31 (Figure 15) stands in the northwestern part of the cromlech. Its decoration had not been reported by previous studies, and therefore it is one of the new stelae that we can incorporate in our study. The engravings are located on a convex side facing north. The face has been adapted to the upper and narrowest part of the piece, consisting of two circular eyes with an internal point, one on each side of the face, looking practically upwards. The inner part shows an incised geometric engraving with a central line and several horizontal lines. It thus resembles the upper part of some schist plates -also depicting trapezoidal faces filled with geometric motifs- and even some French statue-menhirs.

Below, a necklace made in bas-relief can be easily seen, as well as the worked area around it to generate the bas-relief. The left side shows the strong blows to break the piece, which is rather more evident below the face, where powerful knapping removed the original surface. This created a polished and trapezoidal finish that emphasizes the volume of the upper part of the piece. This kind of processes of strong knapping and recreation of body volumes has been documented in other megalithic pieces in Iberia.

4.3. Discussion: the archaeological outcomes of the method and the opening of new interpretative trends

The chosen examples are useful to characterize an elaborate system of relief engravings, of which few remains are currently visible to the naked eye. In fact, the most recent revision of the site suggested that the stelae that formed the cromlech were located on the highest points of the site and its western side (Ferraz, 2009, p. 158). The cases discussed here are located in the eastern part of the cromlech. They represent only a part of the documented decorated supports, which confirms that a considerable number of the pieces are stelae crafted and conceived as three-dimensional decorated supports.

A cut and reused support (Menhir 62), one in the process of being restructured (Menhir 31) and another one preserving an important part of the engravings from the oldest phase of the site (Menhir 64) reveal that Almendres was not only the product of sustained activity in the decoration of the supports, but the aggregation of pieces in different moments, maybe from a previous structure. In spite of several archaeological documentation studies, the sequence of aggregation of pieces, as in other areas of the Mediterranean region (D'Anna et al., 2006), has not been considered. This would be necessary after bearing in mind the evidence presented here.

From a cultural point of view, the new images described above change drastically not only the repertory of decorations at Almendres, but that of menhirs in southwestern Europe in general. First, an ancient phase has been detected. This phase is characterised by anthropomorphic decorations accompanied by daggers and perhaps axes, together with pieces decorated with circles, some of them concentric. These are common in open-air

rock art and some European megaliths, especially in Iberia and Brittany. Second, we can confirm a close relationship between the pieces recorded and the statue-menhirs in South France, as we proposed some time ago to explain part of the reused pieces in the dolmens of South Iberia. The Olvera and Anta de Telhal stelae, both reused as slabs in grave chambers in Cadiz (Spain) and Évora (Portugal), are good examples (Bueno-Ramírez et al., 2015b, 2013) (Figure 16). A sheathed dagger hanging from a band around the neck, in bas-relief, and classic measures (Rodríguez, 2015) has been identified for the first time in the Iberian Peninsula. They share with them the position of the faces and the eyes in the upper part of the rock as well as the necklaces and the breasts.

In the Iberian Peninsula, some megalithic archaeological contexts are known to contain decorated pieces from previous open-air structures. The recent documentation of a ceremonial centre with menhirs and decorated stelae at Soto Dolmen (Huelva, Spain) is a remarkable reference. The engravings on the stelae include T-shaped faces in relief and circles carved in a phase previous to their incorporation in the dolmen at the beginnings of 4th millennium cal BC. Weapons, belts and clothes were added to the stelae after their relocation in the grave. This set of actions can be interpreted as a gesture to highlight the individuality of the represented images. This whole process took place during the 4th millennium and most of the 3rd millennium cal BC in several European sites (Bueno-Ramírez et al., 2018; Eogan, 1997; Stout and Stout, 2008).

The aggregation of pieces at Almendres can now be seen as the result of representing human images on older pieces. Their quantitative representation and antiquity in Iberian contexts confirm the prominent role of south-western Iberia in the creation and expansion of symbolic narratives fixed in rock images. The Atlantic links that have been traditionally considered in the interpretation of Western Iberia Prehistory must be added to the inner routes that would connect this region with South France, where similar pieces to those at Almendres are found in more recent chronologies, revealing a unique material development (Bueno-Ramírez et al., 2015a; Maillé, 2010).

5. Conclusions

Many teams are working on achieving a mechanical system for data recording. As we have previously stated, the most evident concern is the scarce definition of the graphic documentation obtained (Bueno-Ramírez et al., 2014; Cassen et al., 2013). For this task, we have employed a protocol, 3DMeshTracings, that is able to manage a certain amount of information with the aim not only of increasing the resolution of graphical outputs, but of observing the finest details of decorations in a way that is significantly superior to other systems currently available. The main advantages of the proposed methodology can be summarized in four aspects: 1) an efficient volumetric recording of decorated megalithic supports, 2) the accuracy and rapidness of the workflow for obtaining interpretable images, 3) the avoidance of contact with the surface of the pieces during the survey work and 4) the minimization of the use of specific and additional illumination during the photogrammetric recording of the pieces.

Furthermore, the method described here decreases significantly the time invested in recording and processing each menhir compared with conventional photographic recording, but also with other digital solutions, like RTi or laser scanning. It now seems feasible to observe all the faces of a piece at a glance, which can be seen as a positive

advance in the recording of this specific kind of monument. We can also use 3D meshes as a support for mapping photographic textures derived from the work of expert researchers. To know the graphic supports, and how to look for decorations, to manage natural and artificial lighting, and, in sum, possess experience, are undeniable skills and added values that can have a positive impact on the recording of prehistoric art through digital methods but also through traditional techniques. A dialogue between both approaches is desirable to achieve proper and complete archaeological documentation.

The present work can be seen as a preliminary advance to the study of Almendres, but also to other cromlechs and isolated menhirs that are currently being studied in South West Iberia. The procedure of recording described here is undoubtedly a resource for assessing the sequences of use of menhirs and “stelae-menhirs”. As other megalithic slabs (Bueno-Ramírez et al., 2016) or objects (Jones et al., 2015), menhirs and “stelae-menhirs” are the final result of a series of tasks that might include the re-making, transformation and maintenance of monuments, whose display and exhibition must have played a relevant role.

The effectiveness of the proposed protocol makes it feasible to produce a high-resolution record that can enable us to compare symbols and reveal associations among the pieces that comprise one of the finest clusters of megalithic art in Western Europe. This work opens a new perspective on the understanding of complex associations of symbols. Therefore, it is desirable that this work should be used to reveal specific social practices that can be put into context thanks to a plentiful archaeological record. The newly recorded motifs suggest that some megalithic sites in western Iberia need to be revised to grasp a more complete insight into their decorations.

Moreover, the outcomes of the “3DMeshTracings” protocol enable other perspectives for the protection of sites like Almendres. Knowing the position of the engraved supports becomes essential for assuring their protection and considering their restoration in a near future. Additionally, the digital nature of the final products makes feasible the social dissemination of the results through digital platforms.

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Figure 1. Simplified workflow of the methodology used in this article, from the recording of information in the field to the production of final 3D meshes.

Figure 2. Details of the point clouds generated through Colmap software running on a GPU cluster. Menhir 64 is taken as an example. A) Sparse point cloud, B) Dense point cloud before cleaning (the surrounding pieces can be appreciated), C) the point cloud once cleaned, and D) detail of the point cloud where the point density can be appreciated.

Figure 3. Meshes generated through Poisson Surface Reconstruction algorithm with different depths and the approximate number of faces generated by each depth. It can be appreciated that depths over a value of 12 generate detailed results. Less detailed meshes generated with depths under 12 are used as regularized surfaces and as sources for comparison through Hausdorff distances. The front side of Menhir 62 (Almendres, Évora, Portugal) is taken as an example.

Figure 4. Calculation of Hausdorff distances taking the front side of Menhir 62 (Almendres, Évora, Portugal) as example. A) Mesh interpolated at a depth of 13, B) Simplified mesh interpolated at a depth of 6, C) Mapping of Hausdorff distance between B and A meshes, D) transformation of C to grayscale.

Figure 5. Visual description of the process for detecting the finer and coarser engravings from 3D meshes and combining both kind of data into a single mesh. Hausdorff distance is calculated between meshes generated at depths of 6 and 13 and 10 and 13, their results are later combined. Menhir 62 (Almendres, Évora, Portugal) is taken as an example.

Figure 6. A possible workflow for producing traces after the calculation of Hausdorff distance. The mesh is coloured considering different intervals of Hausdorff distance. A) Positive values, B) negative values, C) a short interval of positive and negative values close to zero for representing plane areas, D) combination of the three previous steps in a single image and then converted to grayscale. Menhir 62 (Almendres, Évora, Portugal) is taken as an example.

Figure 7. Location of Almendres cromlech, Évora, Portugal.

Figure 8. Lower area (East) of Almendres cromlech, Évora, Portugal. In the background, the plains of Évora, where one of the largest megalithic sets in Europe can be found (Photo: R. de Balbín).

Figure 9. Almendres cromlech plan with the position of the studied pieces (modified after Alvim 2004)

Figure 10. Menhir 62 at Almendres cromlech, Évora, Portugal. a) view of its four sides (3D meshes coloured by Hausdorff distance values), b) photographs of three of its sides (Photos: R. de Balbín)

Figure 11. Details of the objects detected on Menhir 62. A) *L'object* hanging from a necklace and a superimposed crook on the pointed part of *l'object*. B) Details of the crook ordered from bigger to smaller carved on the right side.

Figure 12. Menhir 64 at Almendres cromlech, Évora, Portugal. a) view of its four sides (3D meshes coloured by Hausdorff distance values), b) photographs of its sides (Photos: R. de Balbín)

Figure 13. Menhir 64 at Almendres cromlech, Évora, Portugal. Details of the detected objects. A) circle phases on the front, B) Rectangular shape engraving with upper apex on the reverse side.

Figure 14. Breton and Iberian references for the stelae with upper apex: a) Mané Rotal, Brittany, b) Petit Mont, Brittany, c) D2o support in Dolmen de Soto, Huelva, d) Capstone from chamber J of Barnenez barrow, Brittany, e) support I30 in Dolmen de Soto, Huelva. After Bueno et al. 2018, fig. 8.

Figure 15. Menhir 31 at Almendres cromlech, Évora, Portugal. a) views of its four sides (3D meshes coloured by Hausdorff distance values), b) photograph of its front side (Photos: R. de Balbín), c) detail of the engravings.

Figure 16. a) Trace of the re-used stela at Anta de Telhal, Évora, Portugal (after Bueno et al. 2015a, fig. 3). A dagger can be seen in the right side. b) Re-used stela at Dolmen de Olvera, Cádiz, Spain (after Bueno et al. 2013, fig. 17). It presents a bow in the upper area and a dagger in the lower area.

a

b

c

d

a

b

c

d

Mesh (depth = 6)

Mesh (depth = 13)

Hausdorff distances
(grayscale)

Combined
information

Mesh (depth = 10)

Mesh (depth = 13)

Hausdorff distances
(grayscale)

a

b

c

d

0.65

a

b

a

b

a

b

a

b

c

a

b