Heritage Science

RESEARCH

Open Access

Multi-light photogrammetric survey applied to the complex documentation of engravings in Palaeolithic rock art: the Cova de les Meravelles (Gandia, Valencia, Spain)

Ana Cantó[1*], José Luis Lerma[2], Rafael Martínez Valle[3] and Valentín Villaverde[1]

Abstract

The new phase of study and revision of the Palaeolithic art of the Cova de les Meravelles, as well as the advances made in the field of 3D documentation in recent years, have motivated a new documentation campaign on the main panel full of tiny engraved motifs. The difficulties involved in acquiring and processing data executed using fine and thin engraving techniques indoors, have been solved through a multi-light photogrammetric survey, photographing the main panel surface with five lighting directions, and applying principal component analysis (PCA). This procedure has allowed us to obtain a large corpus of two and three-dimensional data and to improve the documentation base produced 17 years ago after its discovery. In this paper, we present the procedure followed, the enhanced engraving results in the new documentation campaign, its most significant contributions to the complex archaeological survey, and the limits we have found along the procedure.

Keywords: Palaeolithic art, Structure-from-motion (SfM), Photogrammetry, Thin engravings, Superimpositions, 3D

Introduction

Since the end of the last century, with the development of digital non-invasive imaging documentation methods and the first efforts to reproduce three-dimensionality tracings in parietal art [1], documentation techniques in sites and panels with Palaeolithic art are becoming essential in archaeological surveys. In this sense, an increasing number of research teams have implemented strategies for combining two- and three-dimensional techniques and have also proposed the need to incorporate an analysis of the morphology of the support in studies of rock art [2–6].

Close-range photogrammetry and laser scanning are the most recurrent options for incorporating three-dimensional (3D) technologies in the study of prehistoric art, due to the multiple advantages that both present in terms of their accessibility and development [7]. Their use offers a vast range of possibilities in the study of Palaeolithic parietal assemblages, from the reproduction of the motifs and the elaboration of tracings [4], the analysis of taphonomic processes that influence their state of conservation [8, 9] to the elaboration of archaeological or "technical" tracings [10] and the study of panels with complex superimpositions [11].

One of the difficulties that new documentation and image processing techniques have had to confront is the documentation of thin engravings in contexts where, in addition to the difficulty of legibility and visibility of the panels, there is a total absence of natural light. In this regard, several authors have proposed different 3D documentation methods adapted to each specific case, obtaining favourable results [6, 12–16]. However, the problem

*Correspondence: ana.canto@uv.es

[1] Department of Prehistory, Archaeology and Ancient History, Universitat de València, Avda. Blasco Ibáñez, 28, 46010 Valencia, Spain
Full list of author information is available at the end of the article

of documenting panels with very thin engraved incisions is still present [16].

The Palaeolithic art panel of the Cova de les Meravalles is composed of hundreds of engraved traces that are superimposed, resulting in a complex palimpsest whose primary execution technique is thin and shallow engraving. Immediately after its discovery, a photogrammetric survey of the ensemble was carried out. This combined close-range photogrammetry and multiband photography with variable incident light (multi-light photogrammetry). The images were processed using advanced image processing tools, including principal component analysis and colour balance. This resulted in a mosaic of orthographic images, an enhanced composite metric image characterising the whole set of engravings and a simplified 3D model [17].

The Meravelles parietal assemblage is currently being revised, and the new work, as well as advances in documentation and image processing techniques, have motivated a new campaign of work at the site to obtain more precise documentation that will allow us to achieve the objectives of this new phase of the study: to obtain a visualisation tool that enables, on the one hand, a good reading, for the research and interpretation of the site and, on the other hand, which facilitates the sharing of the results obtained, emphasising the value of the rock art as part of our cultural heritage.

In this paper, we present the results obtained in the areas of most interest and in which the visualisation of the engraved traces is diverse, optimal and non-optimal. The same procedure is being systematically applied to the analysis of the whole ensemble and is currently being carried out.

Case study: Cova de les Meravelles (Gandía, Valencia)

The Cova de les Meravelles (Gandía, Valencia) is located in the Serra de la Falconera at an altitude of 200 m and at a distance of 6 km in a straight line from the Cova del Parpalló.

Archaeological work in the cave began in 1932. Members of the Servei d'Investigació Prehistòrica de la Diputació de València (SIP), including Professor Luis Pericot, were in charge of starting the work in Meravelles and other caves in the province [18]. At that time, the work focused on the outside of the cave, where part of the sediment that had been extracted from the site at the beginning of the century could still be found. In this area, they were able to recover Neolithic pottery and apparently the Palaeolithic lithic industry [18, 19].

In 1953 the SIP team returned to the excavations at the site, this time under the direction of Enrique Pla Ballester. The discovery made by Gurrea Crespo, Local Commissioner of Archaeological Excavations in Gandía, of a small lateral gallery located to the left of the cave entrance, motivated the work was focused on this space [20, 21]. The excavation results were quite successful because, as this area was found intact, it was possible to establish a stratigraphic sequence consistent with that recorded at other sites in the region. Under a superficial level of disturbed soil with cardial pottery, a fragment of a Campaniform vase and Neolithic lithic industry, it was observed, according to the terminology in use at that time, a Solutrean-Gravettian stratum with Epigravettian material (layer 1), another Solutrean-Gravettian level without Epigravettian pieces (layer 2), a third Solutrean (layer 3) and, finally, another Gravettian, which extended to a depth of 1.30 m (layers 4 to 7) [21]. Thus, the Upper Palaeolithic occupation was clearly defined.

The discovery of the parietal art took place in 2003, when the archaeologist Carles Miret noticed its existence in an area located 10 m from the entrance. One of the obstacles to documenting correctly and analysing the figures was their state of conservation. The calcite covering over the engraved motifs impeded their identification on a large part of the surface, so, after verifying that the stalagmitic covering could be removed without damaging the motifs, the Generalitat Valenciana, through the Instituto de Arte Rupestre, in collaboration with the Museo Arqueológico de Gandía and the Departamento de Prehistoria y Arqueología de la Universitat de València, financed the restoration and cleaning of the panel, which was carried out by Eudal Guillamet with the participation of members of the Valencian Institute of Restoration. The work focused on the main panel of the cavity [22].

In 2005 the discovery was the subject of a preliminary note by V. Villaverde, J. Cardona and R. Martínez Valle, which reported the presence of figurative motifs in the main panel of the cave [23]. A few years later, a group of 20 zooforms was documented in the main panel, as well as a series of thermoluminescence dating that revealed a minimum age for the engravings of 18.106 ± 2.534 years. This suggests their Palaeolithic chronology and their attribution to the Pre-Magdalenian phase of the Palaeolithic artistic cycle [22].

The main panel and its limits: characteristics of the support and execution technique of the Palaeolithic motifs

The karst system develops over a long geological sequence characterised by the alternation of limestone and dolomite deposits that originated in the early Upper Cretaceous. The support on which the artistic manifestations are located is limestone; it is a surface where water action is constant, producing the formation of calcium carbonate crystals that have been deposited on the surface throughout the life of the karst. When the parietal art was discovered, a stalagmitic crust covered most of the surface, revealing a few engraved lines and the identification of a few figurative motifs.

The restoration work on the panel, which covers some 3 m^2, was carried out in five campaigns and consisted of the mechanical removal of the layers and incrustations of calcium carbonate that covered the grooves, and which at that time impeded the correct visualisation of the panel. The results were very positive, as they made it possible to considerably increase the decorated surface, as well as the number of motifs inventoried (Fig. 1). However, the restoration of the panel had certain limitations due to the previous degradation of the rock, so there were areas where the calcium carbonate could not be removed in totality to avoid damaging the artistic manifestations.

The motifs documented at Meravelles were executed using the technique of engraving, predominantly with a simple stroke, and on a few occasions using multiple strokes for the execution of specific details. The singularity of the group resides in the technical characteristics of the engraving which, for the most part, is characterised by a thin, shallow line that is hardly perceptible to the eye. A more detailed examination of the execution technique allows us to distinguish up to three types of strokes, which are distinguished by the width of the line and its depth, contributing to the more or less visibility of the motifs. Firstly, we can distinguish a type of stroke of larger width and depth applied to very few figures (1); secondly, a simple, thin and shallow stroke (2); and finally, a very shallow and almost superficial type of stroke (3), the last two being the most abundant types (Fig. 2).

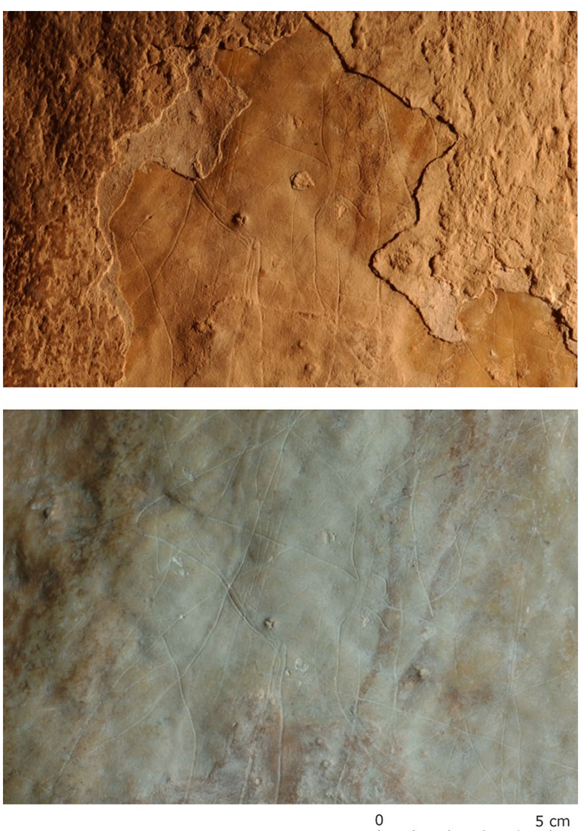

Fig. 1 Detail of the sector where the aurochs M-7 is located before and after panel restoration

The nature of the support and the technique used to execute the motifs are two aspects that have conditioned the whole documentation process, from data collection and later processing to the final result. As far as the support is concerned, we must bear in mind that, on the one hand, we are in an area where the levels of humidity are very high, which can alter the chromatic tone of the surface considerably at certain times of the year and even make some of the engraved lines invisible (Fig. 3). On the other hand, the surface is not uniform, and the different sectors into which the panel is divided are at different depths (Fig. 4). Furthermore, the problems encountered during the restoration work, which prevented the removal of all the remains of calcium carbonate encrusted in the grooves, are another disadvantage in terms of documenting these areas of the panel and being able to show the order in which the figures are superimposed. As regards the execution technique, we must take into account that the thinnest strokes, especially type 3, are very difficult to capture. This limit has been resolved to a considerable part thanks to the new documentation, although it is an aspect that we must continue to work on in order to improve the resolution of these specific areas.

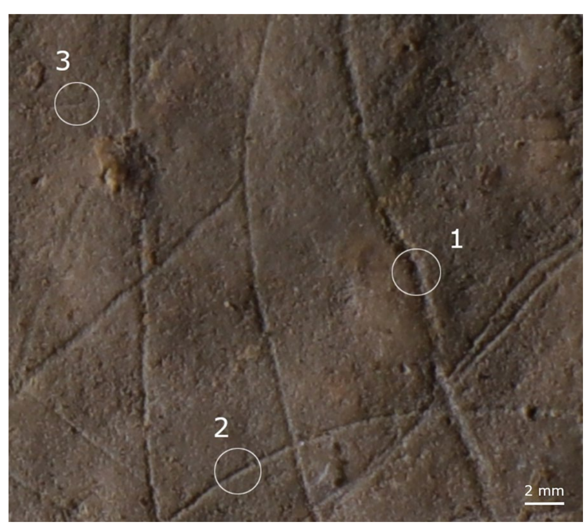

Fig. 2 Types of documented strokes (close-up photography)

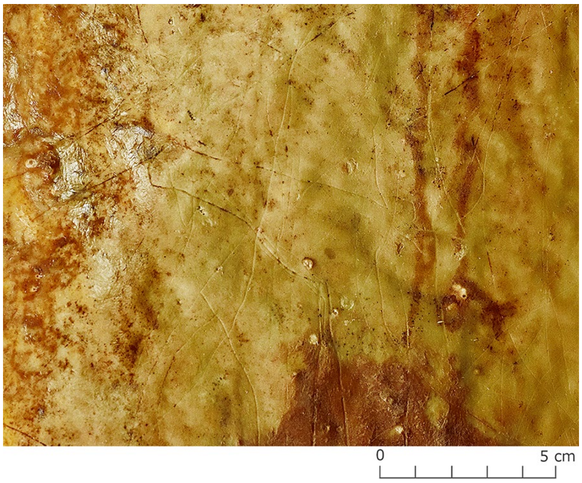

Fig. 3 Detail of the sector where the aurochs M-7 is located, affected by water action in August 2020

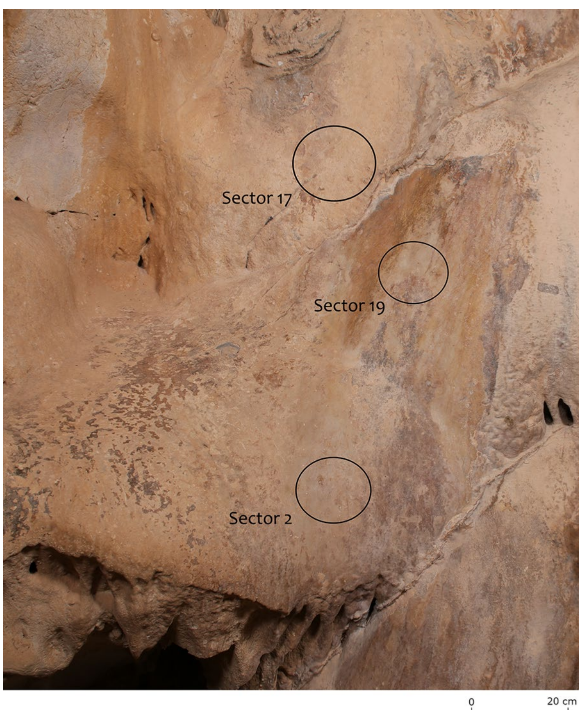

Fig. 4 Overall picture of the main panel and indication of the sectors detailed in this work

Materials and methods

A high-resolution single-lens reflex camera Canon 5DSR with a resolution of 8688 × 5792 pixels equipped with a Canon EOS EF 24 mm was used to get the imagery. Two sets of images were considered for the main panel (Fig. 3), one close-range at 2 m able to yield a low-resolution GSD equal to 0.300 mm, and another close-range set at 0.5 m to deliver a high-resolution GSD of 0.050 mm. The high-resolution images will be used to document the tiny engravings with the help of raking light, as will be presented next in this section. The handle light was a Nebo Big Larry Pro (500 lm). Image processing was undertaken with ENVI software. Agisoft Metashape software was used for 3D modelling and orthorectification.

For fixing the scale on the panel, a 20 cm calibrated scale bar was used to scale the eventual 3D model and orthoimagery. The scale bar was moved across the panel to fix and control the scale of the main panel.

The methodology followed from data acquisition to final deliverables is presented in Fig. 5.

The main panel was divided into 25 sectors, taking five images per sector at 0.50 m from the wall. For each sector, the camera was pointing orthogonal to the central part of each sector. The camera was mounted on a tripod to take the five close-range multi-light imagery (Fig. 6): four main lighting directions with raking light (simulating east, north, west, and south), and the fifth one with orthogonal light that creates a flat scene, covering each image a surface of about 15 cm × 10 cm.

Despite using a tripod, the data acquisition was on top of the scaffolding. Therefore, some small camera movements between shots were compensated afterwards with a projective transformation to create multiband imagery with 15 bands (RGB per shot). This process ended with a multiband image per sector from which principal components analysis (PCA) will be performed to extract significant radiometric content in an orthogonal space, minimising radiometric information overlap among imagery. In addition to the PCA, linear stretching was performed on the PC1, PC2 and PC3 to enhance the visualisation of the engravings. Finally, a false colour image was generated with PC1 (red band), PC2 (green band) and PC3 (blue band).

The lighting conditions for data collection are essential, both to solve the problems derived from the nature of the support, characterised by its heterogeneity and irregular geometry, and to capture the finest engravings correctly. In this sense, the method chosen for taking photographs using five different light orientations is really helpful because it covers the overall area with the minimum imaging dataset (north, south, east, west and orthogonal) to register shadows vs no shadows, and their subsequent processing by PCA is very useful to synthesise all the fine and shallow tracings. The direction of the light in five different positions allows us to obtain detailed documentation of each sector and to have a complete and uniform view of all the areas regardless of the shallowness and orientation at which the very fine incisions are located. It is also decisive for later treatments using PCA, which

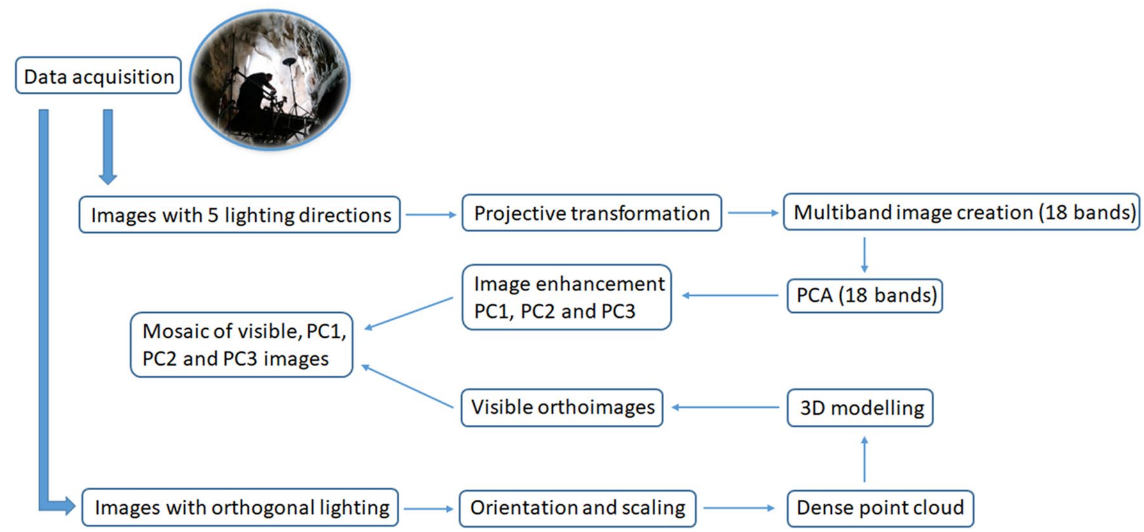

Fig. 5 Pipeline showing the multi-light close-range photogrammetric processing with the close-range images and merging onto the 3D model

completes this process by providing us with all the information captured in the photographs in a unique image. To make the 3D model of the main panel and the final orthoimage mosaic, a state-of-the-art photogrammetric Structure-from-motion (SfM) survey was carried out. The purpose was to obtain a high-resolution point cloud, as a preliminary step to create the eventual 3D model and the final orthoimage mosaic in five layers, the visible one with the orthogonally illuminated images, the first three bands of the PCA (PC1, PC2 and PC3), and the false-colour PCA (PC3 for the red band, PC2 for the green band, and PC1 for the blue band).

Results

The documentation obtained from the data acquisition carried out on the main panel at Meravelles is presented below:

- Photographs were taken with five light orientations at short distances from each sector into which the panel was divided (Fig. 6).
- General photographs of the area where it was located.
- Multiband images, used for the PCA of each sector (Figs. 7 and 8).
- 3D model of the area where the panel was located.
- Six orthoimages (two visible bands + 4 PCA bands) (Figs. 10, 11 and 12).

The photographs with five light orientations are the base of the data collection and are the starting point from which the multiband image of each sector was generated. As mentioned above, given the difficulties involved in observing and documenting thin and shallow engravings in a subterranean context, this strategy was very useful since it allowed us to multiply the points of view of the same sector, complementing each other's images.

A PCA was carried out on the multiband image (15 bands). According to the eigenvalues, the first three components have shown more significant information on each sector (> 95%) since, from the fourth, the noise generated in the image increased substantially. The aim of this process was to accentuate as much as possible the contrast between the engraved traces and the support and, in this way, to obtain a complementary corpus of data for the study of the superimpositions and the elaboration of the panel tracing. For this reason, an enhancement was also carried out on PC1, PC2 and PC3. For this purpose, different image processing tests were carried out using the ENVI software and finally, the best results were obtained by changing the distribution of the values by linearly stretching the data in the input histogram of the image.

Regarding the detailed images of each sector, we have observed that the information provided by PC1 is more significant than in PC2, as it showed a larger surface of engraved traces. However, the thinnest traces were lost and more challenging to capture. PC2 images retained the minuscule detail, showing only the widest and deepest strokes. Finally, PC3, despite the noise generated in this image, offered the most remarkable contrast between the traces and the support, and enhanced them. The best results and the ones that allowed better visibility of the

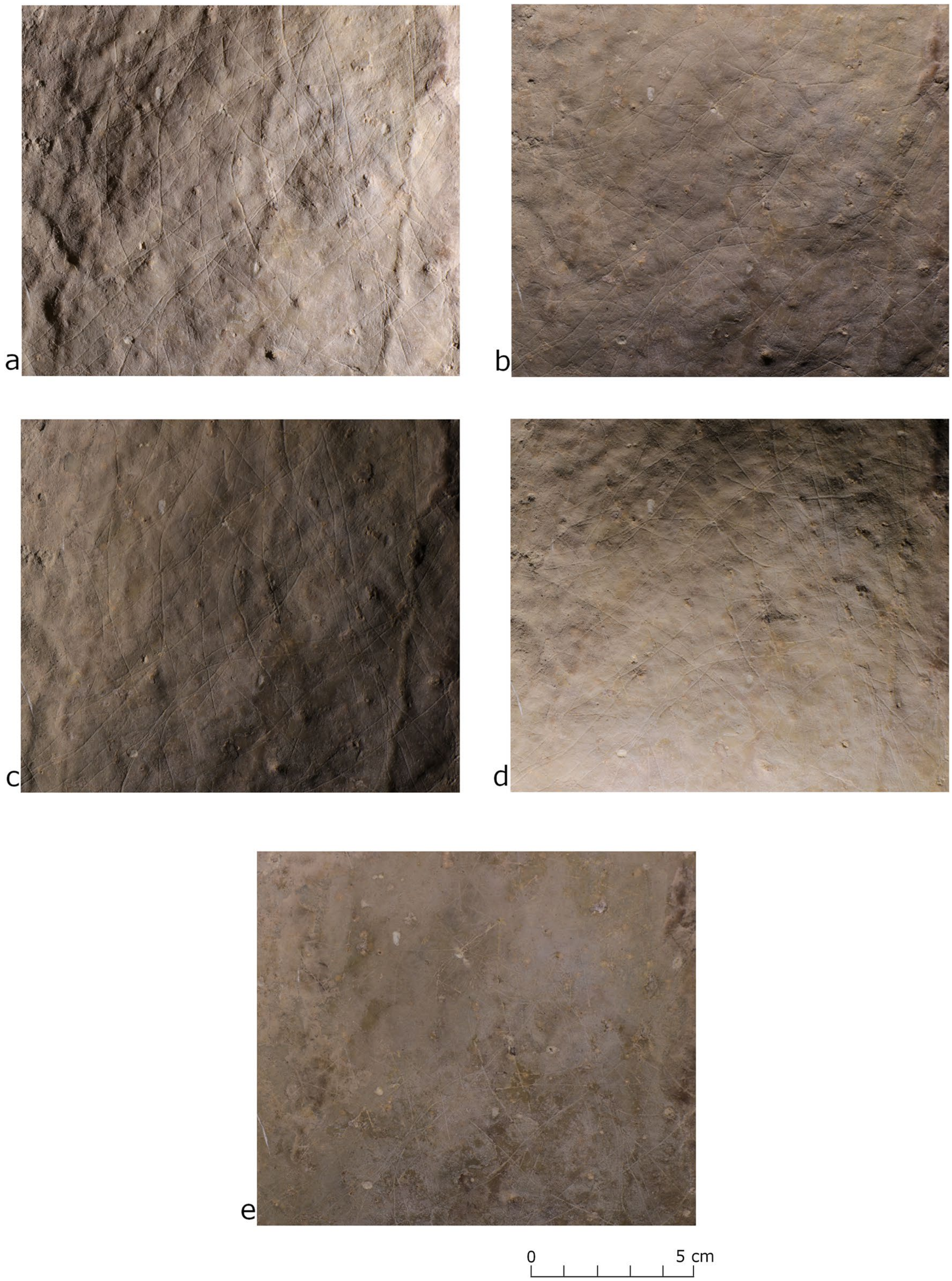

Fig. 6 Detail photographs of sector 2. Lighting directions from: **a** east; **b** north; **c** west; **d** south; **e** orthogonal

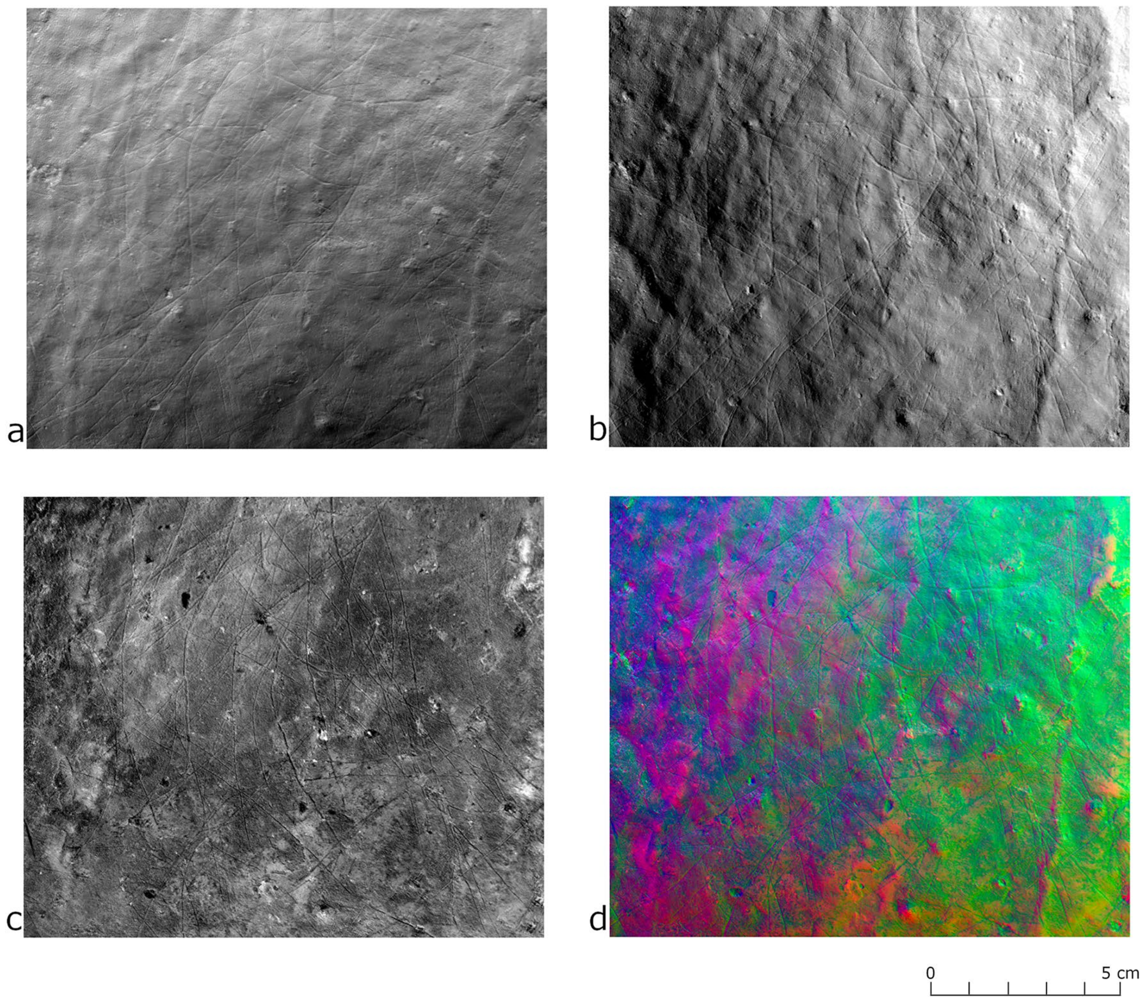

Fig. 7 Principal components analysis (PCA) for sector 2: **a** PC1; **b** PC2; **c** PC3; **d** false colour PCA (PC3, PC2, PC1)

engraved traces, providing a higher level of information, were achieved after combining them into a false colour PCA image, assigning PC3 in the blue band, PC2 in the green band and PC1 in the red band (Figs. 7d and 8d).

The advantage of processing the detail images by sectors through PCA with respect to the original colour images consisted in the contrast generated between the engravings and the support when working in greyscale. With this treatment, the support over-enhances and, therefore, the vision of the context is lost. That is why it is highly recommended to deal with two, the visible and false colour PCA simultaneously.

Finally, six orthophotos or digital orthoimages were generated: the first one at low resolution in true colour RGB of the panel with the images taken at a greater distance (ground sample distance—GSD—of 0.3 mm); and the rest at high resolution (GSD of 0.05 mm). Regarding the high-resolution orthoimages, one was taken in true colour RGB using the orthogonal lighting images (Figs. 10a, 11a and 12a). The rest using the first three principal components, PC1, PC2 and PC3 enhanced respectively, and finally, the combination of these into a false-colour orthoimage, obtaining in this last false-colour image the most significant degree of detail of the study area (Figs. 10b, 11b and 12b).

Discussion

Methodological review

Despite the variety of processing stages evolved from Lerma et al. [17], the developed methodology has proven to be still valid for documenting extremely tiny and faint motifs, hardly visible with the naked eye, unless multidirectional raking lighting is applied during observation. The authors considered the proposal of digital nightlight long photography presented by López-Menchero et al. [15], but the requirement of

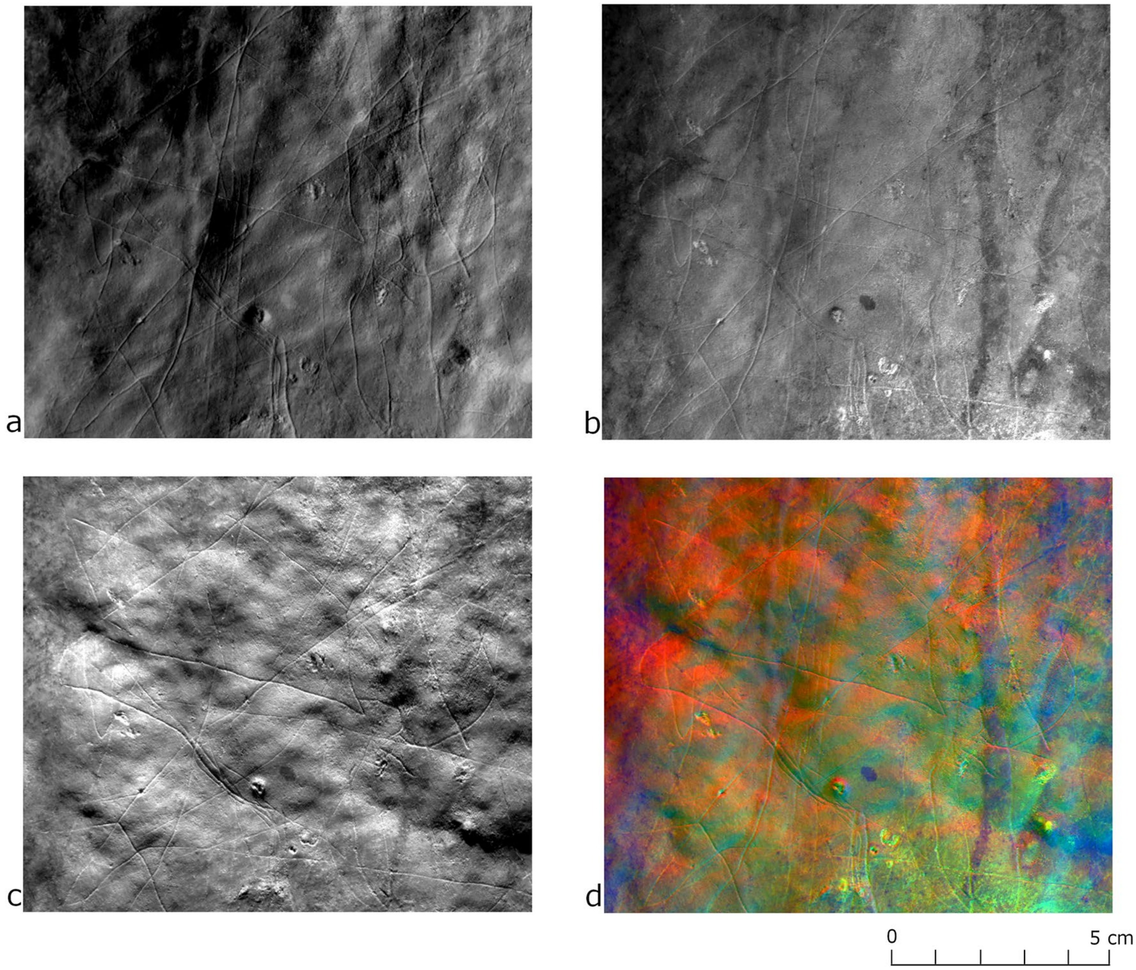

Fig. 8 Principal components analysis (PCA) for sector 19: **a** PC1; **b** PC2; **c** PC3; **d** false colour (PC3, PC2, PC1)

long exposure times invalidated the technique as the scaffolding was somewhat unstable. They also tried high-end structured-light scanning but also failed to track the tiny motifs.

The application of multiband image processing and photogrammetry with the five close-range multi-light imagery (Figs. 7 and 8) in five main lighting directions (four raking positions simulating east, north, west, and south directions) and one additional with orthogonal light creating a flat scene is a kind of simplified reflectance transformation imaging (RTI) technique [24], despite the fact that the usage of domes is not allowed on the panel in the cave, and its morphology is not flat at all. Thus, both RTI and highlight-RTI (H-RTI) were rejected. In addition, as the tiny engravings do not allow for the high-resolution 3D modelling of them, but the whole panel, virtual RTI (V-RTI) as well as other enhancing tools such as morphological relief models and visualisation effects (hill shading, sky-view factor, high-pass filtering…) might have been considered to be applied on the virtual 3D models [25–27].

Besides, automatic photogrammetric 3D modelling has enormously evolved in the last 15 years. Nevertheless, the alerts and recommendations from Remondino et al. [26] are still valid nowadays to yield accurate and reliable deliverables, not only fancy visualisations. The proliferation of drone photogrammetry with different nominations (UAV, UAS, RPAS…) is paramount, but this point is outside the scope of this paper for rock art panels indoors and without daylight. Reprocessing the original dataset from Lerma et al. [17] yielded higher resolution 3D point clouds, 3–5 times larger, but still not comparable with the current ones using a 50.6 MP instead of a 12 MP camera.

The use of a flashlight in caves for rock art documentation has proved to be a very effective resource for obtaining quality photographs [16]. The flashlight has been only used for macro photography of small areas to identify superimpositions, serving as a complement to all the documentation generated. But the usage of a flashlight for this multi-light photogrammetric survey was avoided, because there is a need to have complete control of the scene under the lighting conditions (under an irregular but continuous surface) before taking the shots. In fact, once the ideal directional lighting conditions are set on the scene, the pictures are taken. And this point cannot be achieved with flashlight.

Contribution of photogrammetric acquisition to the case study

The new documentation campaign provided a broad documental base that allows us to update and improve the one carried out in 2005. By combining photogrammetric and two-dimensional digital image processing techniques, we will be able to produce a detailed reproduction of the Meravelles parietal assemblage and obtain a complete corpus of data for the integral analysis of the panel. In this way, we have been able to cover the needs of study at the documentary level, analysis of the stratigraphy of the parietal engravings, their degree of conservation over time and, finally, in the area of diffusion.

All the information generated, from the two-dimensional images obtained in the data acquisition to the reproduction of the 3D model of the support, are the working tools to generate all the necessary documentation that, as has been pointed out in previous works, a comprehensive study of parietal art should contain, including the individual tracing of each motif, the overall representation of the group, its relationship with the support and a reproduction of it that allows us to observe the composition from different perspectives [4].

The detailed photographs taken with five different orientations of light are an essential tool for analysing the assemblage during the elaboration of tracings, as well as in the study of the parietal stratigraphy, since they provide a high level of detail and a detailed view of the traces and superimpositions.

Regarding the detailed photographs processed with the ENVI software and those on which the PCA was carried out, we think that, depending on our objectives, the images in which PC3 was enhanced can be used as supporting material, complementary to the orthoimages during the tracing process, as they are the most successful in defining the engraved traces. However, PC3 images are not helpful in the study of the parietal stratigraphy of the panel since, by emphasising the contrast to highlight the engravings, the traces do not preserve their morphology. In this sense, PC1 and PC2, even assuming the loss of information due to the absence of the thinnest traces and the most difficult to capture, would be appropriate for this purpose, given that the most visible ones show the degree of superimposition correctly. The best results were obtained with the combination of PC1, PC2 and PC3 bands into a single false colour image with three bands. The false colour PCA image provided a higher level of information and a greater level of detail. It was an essential tool both in elaborating the tracing (Fig. 9) and in the study of the parietal stratigraphy, as it shows the superimpositions between motifs most clearly (Figs. 10b, 11b and 12b).

The high-resolution 3D model obtained, with a GSD of 0.03 mm, is not a helpful tool for the elaboration of the tracings and the study of the superimposition between traces, since the images were taken at a greater distance from the panel and the degree of approximation was not sufficient to capture the totality of the engraved traces. However, in our study, the 3D model is decisive for analysing the support and obtaining a complete view of the area where the engraved motifs are inserted and, in this way, understanding the interrelationship between them. Macro photogrammetric solutions [28] should be used to substantially increase the resolution of specific areas of the panel, where the legibility could be more complicated, regardless of the complexity and more outstanding work required due to the geometric characteristics, acquisition method and complexity of the main panel.

With regard to the digital orthoimages, our aim was to obtain two-dimensional documentation that would be used as a metric basis for the graphic reproduction of the motifs for their vectorisation. In this sense, the most convenient is the true-colour orthoimage with a GSD of 0.05 mm and the false colour PCA orthoimage obtained from the combination of PC1, PC2 and PC3, in which the level of resolution obtained is the highest (Figs. 10, 11 and 12), providing a better approach. However, as mentioned above, the visibility of the engravings is notably higher in the second one, which captures the finest traces that the true-colour image cannot show (Figs. 10b, 11b and 12b). It is, therefore, the most effective visual tool not only for the correct elaboration of the tracing, as it shows the traces that are more difficult to capture using the orthogonal lighting method, but also for the technical study of the motifs. With regard to the latter question, it is more evident that the false colour PCA orthoimage shows better the different techniques used in the engraving of the figures, as in the case of the multiple trace modality in the execution of certain anatomical details of the zoomorphs (Fig. 11b: 1). To make the final tracing, the 2D documentation generated, both the visible true-colour and the false colour PCA orthoimage mosaics, will be imported in uncompress file formats as two overlapping layers. A vectorisation software will be used to trace each motif on different layers. Eventually, all the 2D tracings will be integrated into the 3D model through the oriented images interchanging the image textures. Therefore, the

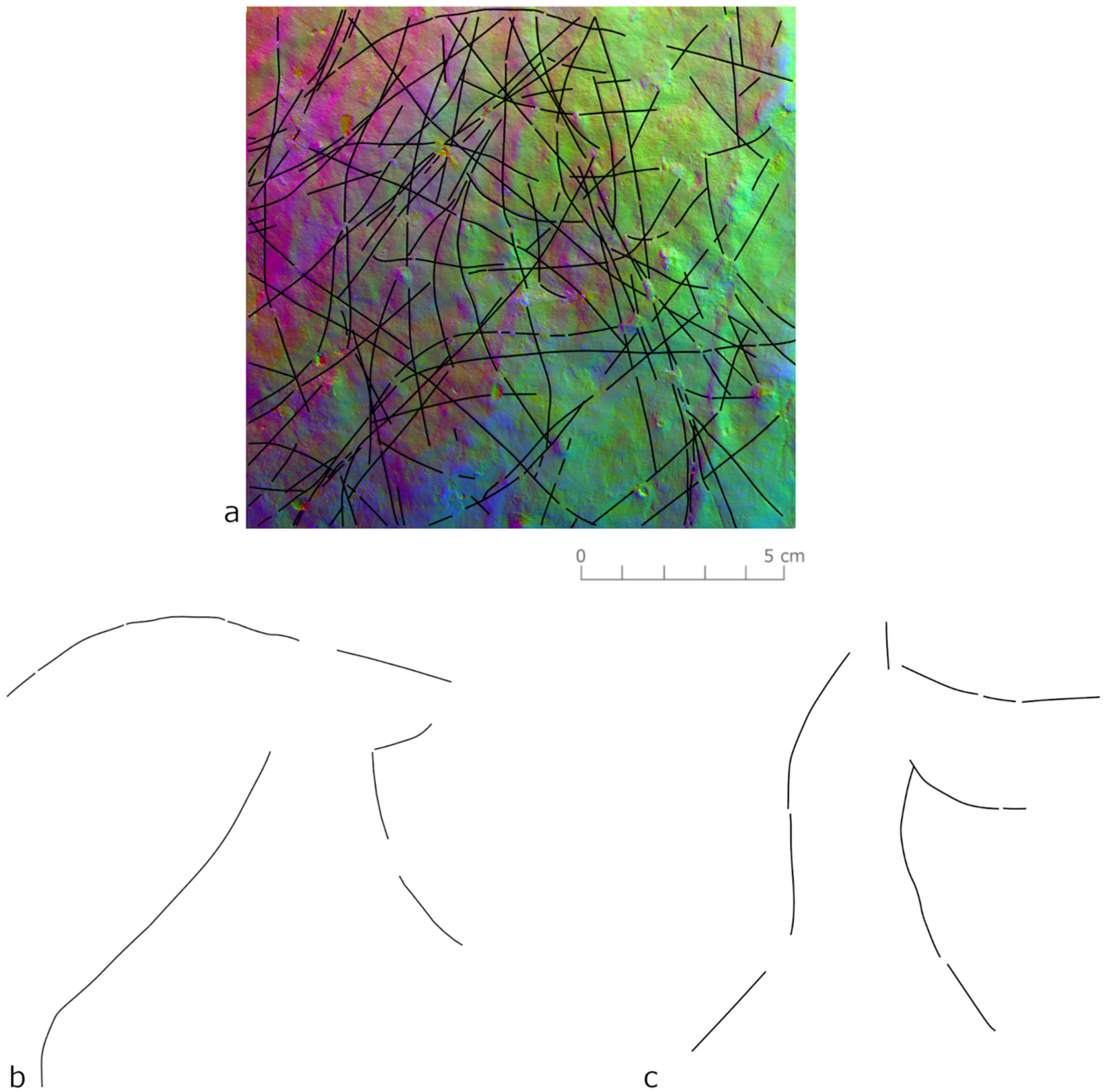

Fig. 9 **a** Tracing of sector 2 made from the combined false colour image; **b** caprid M-13; **c** horse M-14

availability of a solid 3D model is mandatory to achieve proper continuity of the engravings on the overall 2D orthoimage mosaic.

The 3D documentation of panels with prehistoric art is also a valuable tool in the field of conservation, as it allows the monitoring of taphonomic processes that affect the preservation of parietal assemblages and that are the result of the intervention of different biotic, abiotic and anthropic factors [9]. In the case of Meravelles, this point is critical due to the fact that at certain times of the year, there are areas of the panel that are exposed to water dripping and humidity, which can alter the conservation and visualisation of the motifs. For this reason, obtaining a graphic reproduction of the support was crucial in order to have a resource capable of evaluating the current situation of the panel and of being used as a reference for determining its state of conservation in the future. At this point, the 3D model of the support will allow us to carry out this purpose and establish a diagnosis of the measures to be taken for conserving the Palaeolithic engravings. Likewise, both the 3D model and the general orthoimage in true colour with the images taken at a greater distance will be used in the preparation of an archaeological or technical tracing, a method of documentation based on the detailed analysis of the support and which gives an overview, through vectorial mapping, of all the natural processes (relief, dips, humidity, etc.) and anthropic (ancient and recent) that affect the reality

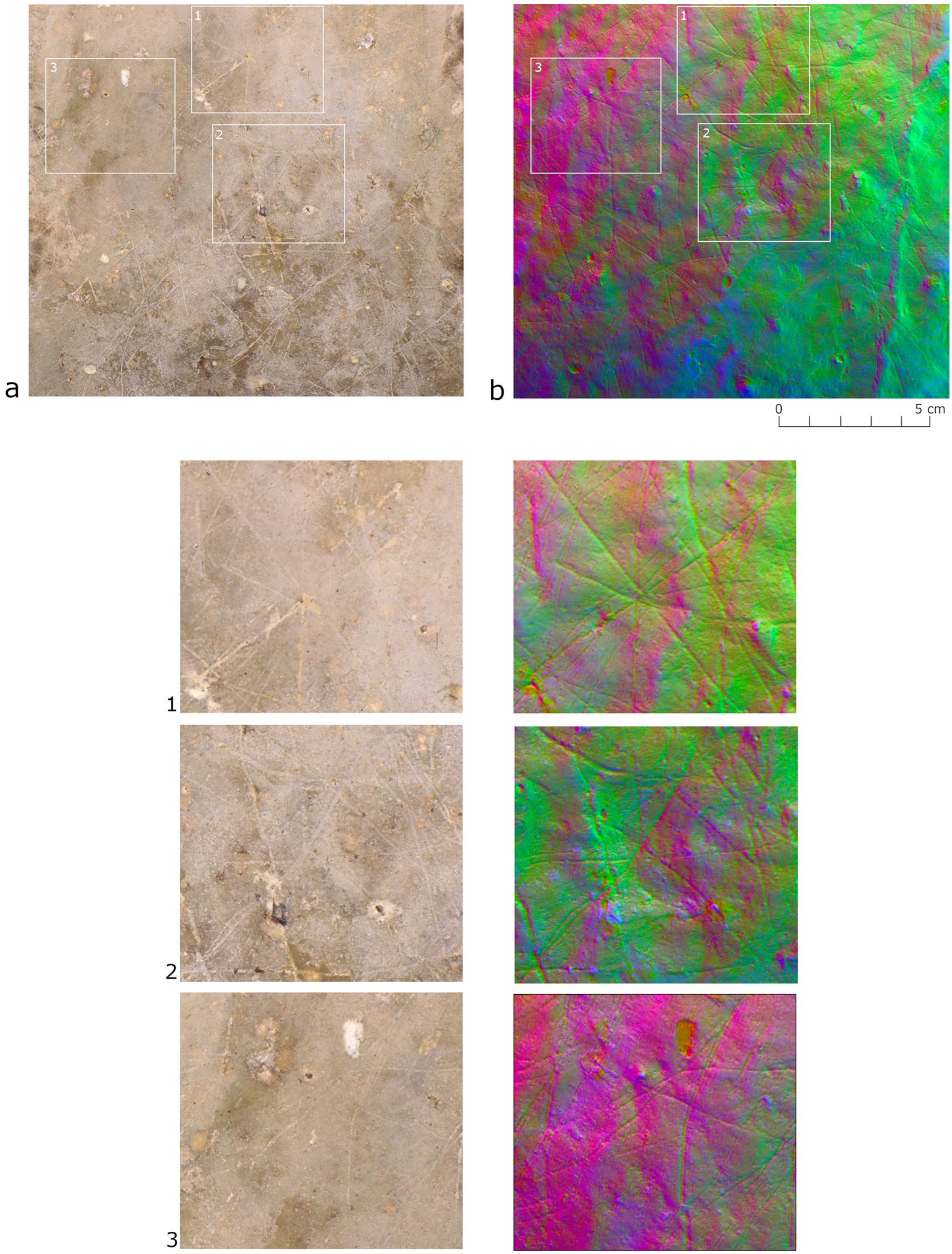

Fig. 10 Sector 2: **a** True-colour orthoimage; **b** False colour PCA orthoimage

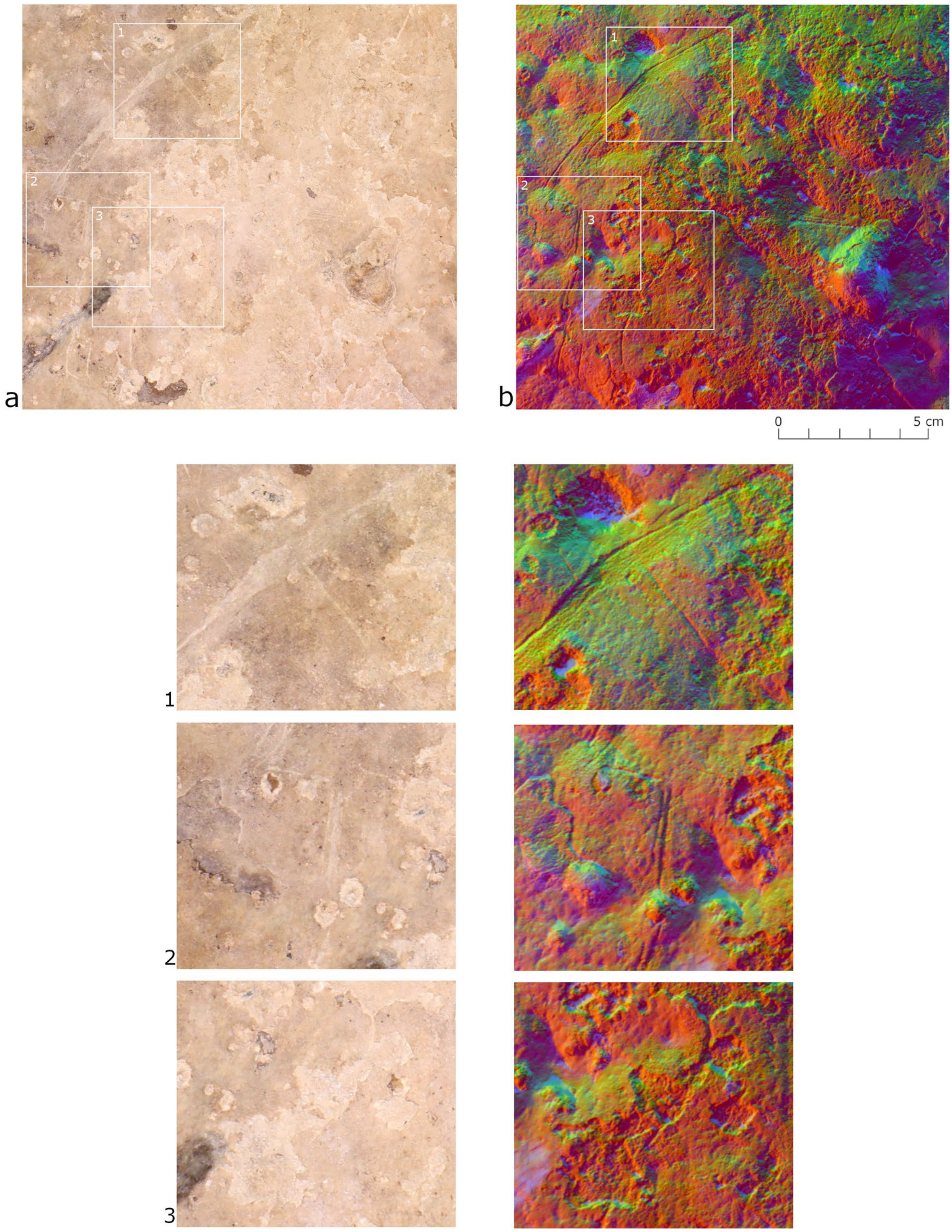

Fig. 11 Sector 17: **a** True-colour orthoimage; **b** False colour PCA orthoimage

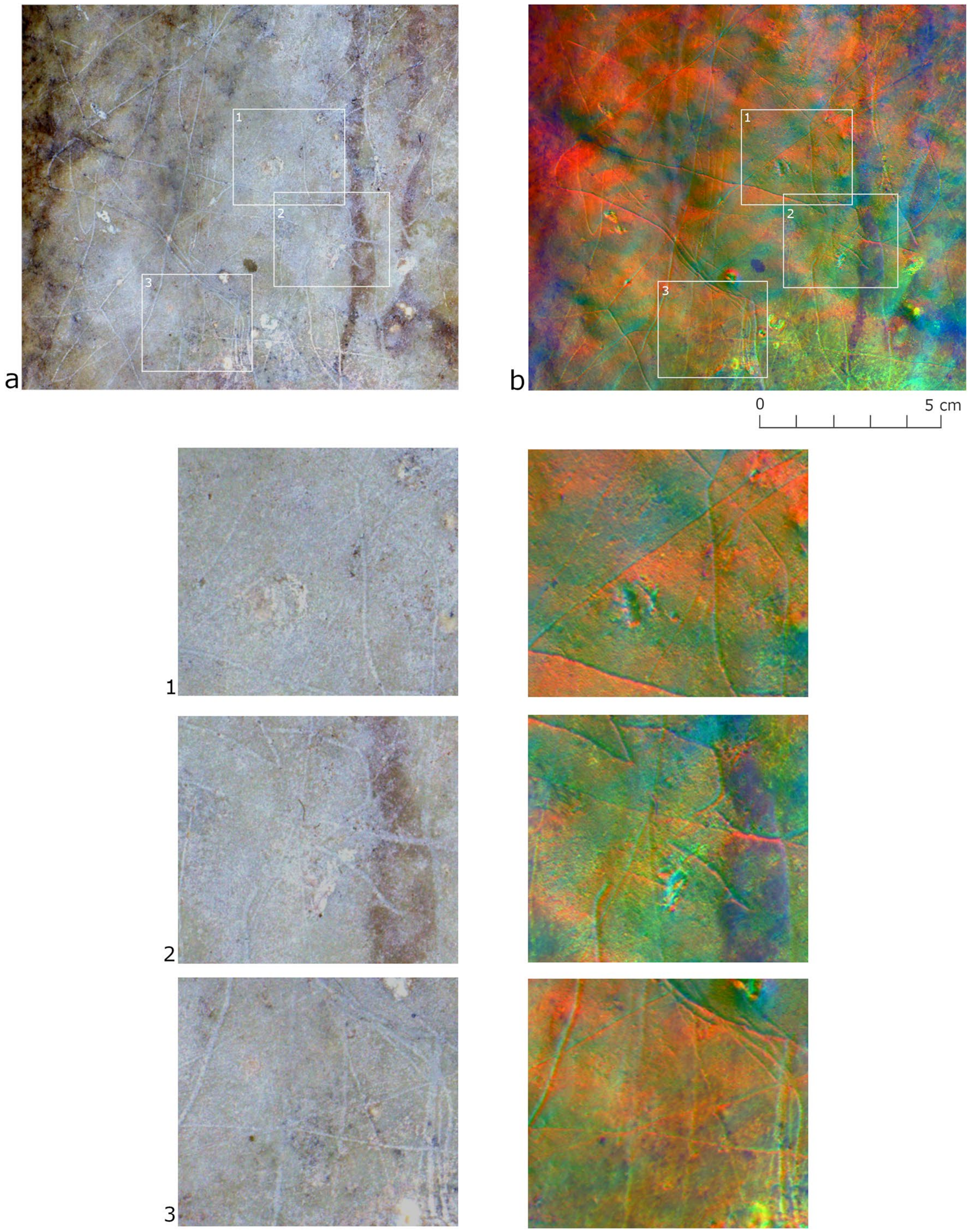

Fig. 12 Sector 19: **a** True-colour orthoimage; **b** False colour PCA orthoimage

of the surface on which the composition is inserted [2, 10, 29].

Finally, in the field of divulgation and cultural heritage, our aim is to try to take advantage of the museum possibilities offered by the new documentation obtained for the diffusion of Meravelles Palaeolithic art. In this sense, there is the possibility of exhibiting the results using panels and audiovisual resources to allow society to discover this part of our heritage and raise awareness of its value and fragility, thus promoting its function as a cultural and educational tool. This part of the work is particularly interesting as the site is currently not open to the public and the access track, which is difficult to cross, is not adapted for visits.

Final valuation and conclusions

This work has shown how multi-light photogrammetry with different instruments (cameras, lighting and software) continues to be a valid method to achieve metric documentation for the study of thin and shallow parietal engravings in caves under complex indoor scenarios (non-flat surface, large irregular panel, that requires mandatory usage of scaffolding). In addition, in our case, it has allowed us to improve the metric results obtained in previous works carried out in the same cave, Cova de les Meravelles, after 17 years.

We have obtained a corpus of two- and three-dimensional data that amply responds to the objectives proposed at the beginning of this work. The new visualisation tools obtained have been capable of showing the most complex areas of the panel favourably, facilitating their reading and subsequent study during the laboratory work.

The most significant contribution in this new recording season resides in the 3D model of the support, which has substantially improved three fundamental aspects: colour, volumetry and metric precision, generating a model with a much higher resolution than that obtained in previous years, with more measuring points and a larger surface area, thanks to the improvements produced in the multi-light photogrammetric documentation field. All this has provided us with realistic reproduction of this small area of the cave and, therefore, a tool that facilitates its study in the laboratory.

The production of a larger number of orthoimages with different image processing techniques has increased the documentation base available in 2005, when only one greyscale orthoimage emphasising PC3 was generated. This allows us to work with a very extensive documentation base that can be adapted according to the needs of each phase of the study: the elaboration of the tracing, the identification of the motifs, their relationship with the support and the detailed study of the composition of the panel. The new documentation, and especially the false colour PCA orthoimage, has helped us to improve the previous tracing, opening new perspectives in the study of the parietal art of Meravelles and has allowed us to define new motifs that are currently in the process of identification. The limitations we have encountered, especially in the correct reading of the parietal stratigraphy in small areas of the panel, have been solved by using flashlight to obtain macro photography in these zones, complementing the documentation achieved.

The methodology used in the new phase of the study, from data collection to its subsequent treatment integrating new image processing methods not used at the site until now, has been adapted to the specific conditions of the main panel at Meravelles. However, it could open up new perspectives for the study in other areas with parietal art recently discovered in the cave, where the execution technique is identical to the main panel, as well as in other sites where the documentation of fine and shallow engravings involves similar limits as those found in our study.

Acknowledgements
The authors gratefully acknowledge the financial support of Ministerio de Ciencia e Innovación and Generalitat Valenciana.

Author contributions
AC and JLL wrote the article with contributions from all authors. JLL carried out the documentation, data processing and methodological review. AC, VV and RMV were responsible for the interpretation of the data obtained, the evaluation of the results and their contribution to the study of the site. All authors read and approved the final manuscript.

Funding
This work has been part of the project HAR2017-85153-P ("Síntesis del Paleolítico medio y superior en Valencia y Murcia: aspectos cronológicos, paleoambientales, económicos y culturales") and the programme PRE2018-085961, financed by Ministerio de Ciencia e Innovación, FEDER y FSE, as well as the project PROMETEO/2017/060 ("El pasado lejano: aproximación a la conducta y la ocupación del territorio en el paleolítico valenciano") financed by Generalitat Valenciana.

Availability of data and materials
The datasets used and/or analysed during the current work are given either in the text or in the cited references.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Prehistory, Archaeology and Ancient History, Universitat de València, Avda. Blasco Ibáñez, 28, 46010 Valencia, Spain. [2]Department of Cartographic Engineering, Geodesy and Photogrammetry, Universitat Politècnica de València, Camino de Vera, s/n, Building 7i, 46022 Valencia, Spain. [3]IVCR+I Institut Valencià de Conservació, Restauració i Investigació, C/ del Pintor Genaro Lahuerta, 25-3ª, 46010 Valencia, Spain.

Received: 2 May 2022 Accepted: 16 October 2022
Published online: 26 October 2022

References

1. Lorblanchet M. Art pariétal. Grottes ornées du Quercy. ed. Rouergue; 2010.
2. Bourdier C, Fuentes O, Pinçon G. Contribution of 3D technologies to the analysis of form in late palaeolithic rock carvings: the case of the Roc-aux-Sorciers rock-shelter (Angles-sur-l'Anglin, France). Digit Appl Archaeol Cult Heritage. 2015;2(2–3):140–54. https://doi.org/10.1016/j.daach.2015.05.001.
3. Corchón Rodríguez MS, Ortega Martínez P, González Aguilera D, Muñoz N, Rodríguez P, Gárate Maidagan D, Rivero VO. Nuevas investigaciones

en la cueva de La Griega (Pedraza, Segobia, España). Aportaciones de las geotecnologías al estudio del Arte Paleolítico. Espac tiempo forma Ser I Prehist Arqueol. 2012;1(5):543–56. https://doi.org/10.5944/etfi.5.5359.
4. Domingo I, Villaverde V, López-Montalvo E, Lerma JL, Cabrelles M. Reflexiones sobre las técnicas de documentación digital del arte rupestre: la restitución bidimensional (2D) versus la tridimensional (3D). Cuad arte prehist. 2013;6:21–32.
5. Feruglio V, Dutailly B, Ballade M, Bourdier C, Ferrier C, Konik S, Lacanette D, Mora P, Vergnieux R, Jaubert J. Un outil de relevés 3D partagé en ligne : premières applications pour l'art et la taphonomie des parois ornées de la grotte de Cussac (ArTaPOC/programme LaScArBx). In: Vergnieux R, Delevoie C, editors. Actes du Colloque Virtual Retrospect 2013. Archéovision. 2015;6:49–54.
6. Fritz C, Tosello G, Perazio G, Péral J, Guichard L. Technologie 3D et relevé d'art pariétal: une application inédite dans la grotte de Marsoulas. In Situ. 2010. https://doi.org/10.4000/insitu.6745.
7. Lerma JL, Cabrelles M, Navarro S, Seguí AE. Modelado fotorrealístico 3D a partir de procesos fotogramétricos: láser escáner versus imagen digital. Cuad Arte rupestre. 2013;6:85–90.
8. Fuentes-Porto A, García-Ávila C, Marrero-Salas E. Casa del Samarín, una estación de grabados rupestres en deterioro. Documentación, análisis y diagnóstico en Los Llanos de Ifara, Granadilla, Tenerife. Virtual Archaeol Rev. 2021;12(24):99–114. https://doi.org/10.4995/var.2021.13810.
9. Ruiz JF. Tecnologías actuales al servicio de la documentación, estudio, conservación y divulgación del arte rupestre. In: Viñas R, editor. I Jornades Internacionals d'Art Rupestre de l'Arc Mediterrani de la Península Ibèrica; 2019. p. 341–73.
10. Fuentes O, Lepelé J, Pinçon G. Transferts méthodologiques 3D appliqués à l'étude de l'art paléolithique: une nouvelle dimension pour les relevés d'art préhistorique. In Situ. 2019. https://doi.org/10.4000/insitu.21510.
11. Feruglio V, Bourdier C, Delluc M, Mora P, Aujoulat N, Jaubert J. Rock art, performance and Palaeolithic cognitive systems. The example of the Grand Panel palimpsest of Cussac Cave, Dordogne, France. J Anthropol Archaeol. 2019;56:101–4. https://doi.org/10.1016/j.jaa.2019.101104.
12. Azéma M, Gély B, Prudhomme F. Relevé 3D de gravures fines paléolithiques dans l'abri du Colombier (gorges de l'Ardèche). In Situ. 2010;13:1–14. https://doi.org/10.4000/insitu.6723.
13. Iturbe A, Cachero R, Cañal D, Martos A. Digitalización de cuevas con arte paleolítico parietal de Bizkaia. Análisis científico y divulgación mediante nuevas técnicas de visualización. Virtual Archaeol Rev. 2018;9(18):57–65. https://doi.org/10.4995/var.2018.7579.
14. Lerma JL, Navarro S, Cabrelles M, Villaverde V. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. J Archaeol Sci. 2010;37(3):499–507. https://doi.org/10.1016/j.jas.2009.10.011.
15. López-Menchero Bendicho VM, Marchante Ortega N, Vincent M, Cárdenas Martín-Buitrago NJ, Onrubia PJ. Uso combinado de la fotografía digital nocturna y de la fotogrametría en los procesos de documentación de petroglifos: el caso de Alcázar de San Juan (Ciudad Real, España). Virtual Archaeol Rev. 2017;8(17):64–74. https://doi.org/10.4995/var.2017.6820.
16. Rivero O, Ruiz-López JF, Intxaurbe I, Salazar S, Garate D. On the limits of 3D capture: A new method to approach the photogrammetric recording of palaeolithic thin incised engravings in Atxurra Cave (northern Spain). Digit Appl Archaeol Cult Heritage. 2019;14:e00106. https://doi.org/10.1016/j.daach.2019.e00106.
17. Lerma JL, Villaverde V, García A, Cardona J. Close range photogrammetry and enhanced recording of palaeolithic rock art. IAPRS. 2006;36(5):147–54.
18. Pericot LL. La Labor del S.I.P. y su Museo en el pasado año 1932. Tirada aparte Memoria oficial de la Secretaría de la Diputación. 1932;1932:1–8.
19. Pericot, L. La Cova del Parpalló (Gandía). Excavaciones del Servicio de Investigación Prehistórica de la Excma. Diputación Provincial de Valencia, Madrid, Consejo Superior de Investigaciones Científicas. Instituto Diego Velázquez; 1942.
20. Fletcher D. La Labor del S.I.P. y su Museo en el pasado año 1953. Tirada aparte Memoria oficial de la Secretaría de la Diputación. 1954. p. 37–38.
21. Pla E. Actividades del SIP (1946 a 1955). Arch de Prehist Levant. 1957;6:191–2.
22. Villaverde V, Cardona J, Martínez-Valle R. L'art pariétal de la grotte Les Meravelles Vers une caractérisation de l'art paléolithique pré-magdalénien du versant méditerranéen de la Péninsule Ibérique. Anthropologie. 2009;113:762–93. https://doi.org/10.1016/j.anthro.2009.09.017.
23. Villaverde V, Cardona, J, Martínez-Valle R. Noticia de los grabados paleolíticos de la Cova de les Meravelles Gandia, Valencia: la importancia del arte solutrense en la Región Mediterránea Ibérica. In: Sanchidrián, JL, Márquez, AM, Fullola JM, editors. La Cuenca mediterránea durante el Paleolítico Superior: 38.000–10.000 Años. 2005. p. 214–225.
24. Earl G, Basford P, Bischoff A, Bowman A, Crowther C, Dahl J, Hodgson M, Isaksen L, Kotoula E, Martínez K, Pagi H, Piquette K. Reflectance transformation imaging systems for ancient documentary artefacts. In: Bowen JP, Keene S, Kia N, editors. Electronic visualisation and the arts. London: BCS Learning & Development; 2011. p. 147–54. https://doi.org/10.14236/EWIC/EVA2011.27.
25. Lymer K. Image processing and visualisation of rock art laser scans from Loups's Hill, County Durham. Digit Appl Archaeol Cult Herit. 2015;2(2–3):155–65. https://doi.org/10.1016/j.daach.2015.01.002.
26. Remondino F, El-Hakim S. Image-based 3D modelling: a review. Photogramm Rec. 2006;21(115):269–91. https://doi.org/10.1111/j.1477-9730.2006.00383.x.
27. Torregrosa-fuentes D, Spairani Berrio Y, Huesca Tortosa JA, Cuevas González J, Torregrosa Fuentes AJ. Aplicación de la fotogrametría automatizada y de técnicas de iluminación con herramientas SIG para la visualización y el análisis de una piedra con relieves antropomorfos. Virtual Archaeol Rev. 2018;9(19):114–24. https://doi.org/10.4995/var.2018.9531.
28. Cabrelles M, Lerma JL, Villaverde V. Macro photogrammetry & surface features extraction for Paleolithic portable art documentation. Appl Sci. 2020;10(6908):1–16. https://doi.org/10.3390/app101969084.
29. Pinçon G, Fuentes O, Bourdier C. Sortir de la grotte L'apport de l'étude des abris ornés du paléolithique supérieur. Nouv Archéol. 2018;154:82–7. https://doi.org/10.4000/nda.5500.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.