



Geometric and radiometric recording of prehistoric graphic expression: the case of Peña Tu (Asturias, Spain)

Luis Teira¹ · Vicente Bayarri^{2,3} · Roberto Ontañón^{1,4} · Elena Castillo⁵ · Pablo Arias¹

Received: 10 September 2023 / Accepted: 22 December 2023
© The Author(s) 2024

Abstract

In the studies on Prehistoric Graphic Expression, there are recurrent discussions about the tracings generated by different observers of the same motif. Methodological issues concerning the role of archaeological imaging are often implied within those debates. Do the tracings belong to the observational data exposition chapter, or are they part of the interpretative conclusions? How can the current technological scenario help solve these problems? In 2017, we conducted new documentation of the Peña Tu rock shelter, a well-known site with an intriguing post-palaeolithic graphic collection documented on several occasions throughout the twentieth century. Our objective was to provide quantifiable and, if possible, objective documentation of the painted and engraved remnants on the shelter's surface. To achieve this, we employed two data capture strategies. One strategy focused on analysing the vestiges of paintings using a hyperspectral sensor, while the other centred on the geometric definition of engravings and the rock support, utilising photogrammetric techniques and laser scanning. These approaches presented various parallax challenges. Despite these challenges, our results were highly satisfactory. We resolved uncertainties regarding the formal features of specific designs that had been subject to debate for a long time. Additionally, we discovered previously unpublished areas with traces of paintings. Lastly, we developed a map highlighting recent alterations and deteriorations, providing a valuable tool for assessing the site's preservation status. In conclusion, by employing advanced technology and comprehensive documentation methods, we significantly contributed to understanding and preserving the prehistoric graphic expressions at the Peña Tu rock shelter.

Keywords Post-palaeolithic graphic expression · Rock art · Hyperspectral analysis · Photogrammetry · Laser scanning

Introduction

From the viewpoint of classical field praxis, before the impact of computer applications, the documentation of a site with prehistoric rock art or with Prehistoric Graphic Expression (hereafter PGE)¹ had as its primary objective to obtain 'reliable tracings' and some good photos of the icons and the surrounding rock support. Within this analogical context of the discipline, successful completion of the task involved producing a cumbersome cellophane filled with coloured lines, which was then scaled with a pantograph or photocopied in parts to create a visually pleasing final image.

The inertia of that procedure justifies the reflection of Peter Ucko in the 1980s, in which he warned us that, with these routines, we unconsciously assume that we all 'know what we are doing and that we have good theoretical support to do it so' (Ucko 1989: 285). Indeed, this apparently

consensual documentation pattern of the PGE, being more or less technical and with an equally common vocabulary, seemed congruent until faced with results generated by other researchers on the same documentation space. If the lines on the cellophane did not coincide (a common occurrence), in what terms was the discussion established? Was one documentation more objective than another? Who was right in drawing the lines?

¹ Although this is not the place to justify the use of this terminology, Prehistoric Graphic Expression (PGE) is used as a descriptive lexical resource, consistent with our research objective (the visual or graphic communication of certain prehistoric human groups) and independent of any reference that might be included in the concept 'art'. It should not be interpreted as a criticism of those who use the term 'rock art', i.e. the vast majority of researchers. Of course, this is not an original formula (Bourrillon et al. 2018), and it is even used in this descriptive sense by authors who are convinced of the relevance of the other (Morales 2005: 61).

‘Original image’ and ‘tracing’. These were the two defining elements of the method. They were essential and, in a certain way, axiomatic, which in many cases obviated the need for definition.

However, from the discipline’s early moments, there has been a framework for reflection on these methodological principles. For example, on the role of the image (Lorblanchet 1993: 330), the concept of fidelity to an ‘original’ (Lemozi 1929: 42), or on objectivity in the tracing process (Aujoulat 1987: 9; Raphael 1986: 133). The issues addressed by these and other authors are still relevant to current research. However, the development of new digital strategies for field work and cabinet processing has helped us to understand, from an unprecedented perspective, the theoretical problems dealt with in that analogical context of the discipline. We can say, then, that reflection born of the digital discussion behaves as a metalanguage which orders the theoretical issues dealt with by classical historiography in another dimension. In other words, the current ability to quantify documentation variables that were previously unapproachable has let us transfer to the field of ‘data’, documentation gestures that belonged, in the classical method, to interpretations. Although, in this context, we have not been aware of this change of role due to a lack of perspective.

Let us take an example: If we analyse a publication on PGE, especially if it predates digital archaeology, although it is easy to identify the internal order of its text (we can isolate an introduction, a descriptive chapter of the observable evidence and a section of interpretative conclusions), it is not unusual for doubts to arise when referring to the role of the graphic set that goes along with this text, i.e. the illustrations, the tracings. Do these belong to the exposition of data, or are they the product of the interpretative conclusions? Compared with what we could show for other archaeological processes, where was the data found in our study? In the cellophane tracings?

What does the current technological scenario contribute to the dialectic of classical documentation (original image / tracing)? During the first 20 years of the digital evolution of the discipline, as a general rule, the specialists, trained in a pre-digital era, saw in the ‘new technologies’ the possibility of being more efficient in the method, ‘the Method’ that is as ever defined by this ‘original image / tracing’ duality. Thus, vector graphic apps effectively replaced cumbersome cellophane and markers.

Three-dimensional models made it possible to create grazing shadows synthetically, using light and shadow maps. With this, our brain understood what was engraved, and the outline of its edges was safely delineated using a vector graphic application with its elegant B-splines. However, the method remained locked in its duality: ‘original image / tracing’, and the tracings still did not correspond between different researchers.

The digital world has gone up exponentially and overwhelmingly our capacity to calculate, store and analyse data. As we say, this has made it possible to quantify previously unattainable variables and multiply the points of view or the documentation strategies of the prehistoric graphic original. Suppose we order these circumstances in a methodological reflection; in that case, the elements that articulated the classical duality of the original image / tracing scenario have been changed in their defining parts and have confirmed the role of a novel third part, i.e. the data.

Let us dwell for a moment on each defining element of the documentation process. On the one hand, we must abandon the idea that at the outset of the process, there is an ‘original’ understood as an image. Any image is a construct of our brain, whether we refer to direct visualisation of the object of study or if we use intermediaries such as specialised radiometric or geometric sensors. From a different perspective, computing has taught us that when we document PGE, we face a complex physical reality from which we extract some particular variable that let us reconstruct the graphic message, i.e. the image. This elective act is subjective, but it can be quantified.

A second intrinsically digital circumstance is that we can now present an abundant and ordered array of data in our method. This factor begins with subjective choices; however, these are quantifiable and reproducible by other researchers once their features have been defined. At the same time, the same observer/researcher can reproduce the variables that define the method in different documentation scenarios. This new method, which we have noted is intrinsically digital, makes the documentation modes in the PGE concurrent with any other general archaeology or science research process.

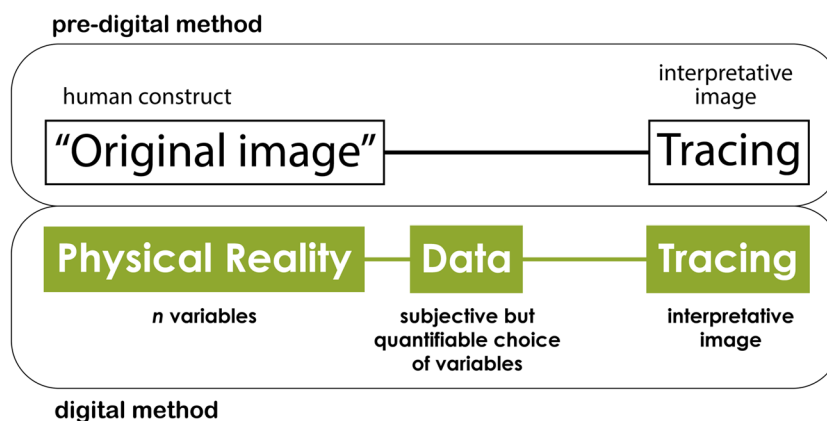
Finally, we must conclude that the interpretive graphic is inescapable. The prehistorian must interpret his data, and that interpretation, in the PGE, will be a graphic document. The difference is that now, we can support this interpretive document in a structured data section (Fig. 1).

However, the structure of this new section (the data) is far from being normalised. The main problem is that in our new habits of digital research, we are reproducing the tics that Peter Ucko talked about in the 1980s of the twentieth century. We use digital terms and concepts we do not define because we carry the false idea that we all know what we are talking about. Electronic tracing, data capture, 3D, 4D, virtual reality, orthoimage and giga-image are frequent terms in current documentation processes.

Do we all have the same understanding when we use them? How does this lack of definition interfere with the distinction between data and interpretation?

Undoubtedly, one of the most common terms and one of the most conflicting is 3D. Let us pause momentarily and reflect on the intrinsically related idea of ‘virtual reality’. Beyond its

Fig. 1 The ‘method’ and the impact of digital environments



Euclidean definition (length, width, depth), most meanings associated with this term concern ‘visual experience’ (Soska et al. 2010; Storrs and Fleming 2021), if we understand as such our ability to discern between sizes and distances. This ability is a complex process based on the maturation of our visual system, which in this case is reproduced in two-dimensional settings through images of successive reproduction in time (4D). Therefore, we are talking about the individual apprehension of a subjective experience. Can we use these virtual reality scenarios to augment and structure our quantifiable data section, making it interchangeable between other observers? On many occasions, researchers/observers claim to understand three-dimensional space within these virtual scenarios as they have never experienced it before. However, when an observation differs from the others, even using this visual tool, how does that affect the discussion? Where is the quantifiable data in virtual reality?

Let us take this theme further, imagining that virtual reality worked ideally, as some hope, and that we could not distinguish the features of physical reality from its virtual version.

Would the problems be over for the researcher? Would the documentation objectives have been achieved? We believe not. Virtual reality would have taken us to the starting point, i.e. the visualisation of a panel. In this virtual or real scenario, we will probably hear interjections such as ‘fantastic’ and ‘impressive’... Everything will be fine until one observer asks: ‘Okay, but what do you see?’ In response, someone will take the initiative and begin to outline a line in the air with their finger. That is the core of the problem in the PGE: to transmit to another observer what one sees or interprets.

Insofar as it immerses us in an individual viewing experience, virtual reality moves us away from the notion of objective and quantifiable knowledge of the data. It invites us to interpret (Guertin-Lahoud et al. 2023: 264). Rather, what we need to create in our documentation process are metric documents (Domingo Sanz et al. 2013), where can these be found in virtual reality?

Let us look at the cases in a general sense. To build a data section in our documentation process, we must move away from graphic solutions that appeal to our ‘visual experience’, which is true for 3D scenarios, such as virtual reality. It also applies to two-dimensional documents, such as synthetic light and shadow maps that, in the same way, appeal to our visual experience to understand what is concave, what is flat, or what is convex, and to be able, based on that, to draw our interpretive B-splines in a vector graphic environment. Here, we would return to the rock-cellophane loop, i.e. physical reality / tracing.

However, this section which is key in bringing our documentation methods closer to other scientific processes that exchange data should be structured from graphic solutions far removed from the ‘visual experience’. These will generate actual interchangeable metric documents. We refer, for example, to the principal component analysis (PCA) (Cerrillo-Cuenca et al. 2014) of raster files generated by specialised radiometric sensors (Bayarri et al. 2021b). We are also referring to the analysis of geometric peculiarities of a 3D model (facet-edges, discrete curvatures, Hausdorff distances, morphological residual models etc.) (Cerrillo-Cuenca et al. 2019; Pires et al. 2014; Rivera Jiménez et al. 2021; Rogerio-Candelera and Linares 2015; Teira Mayolini and Ontañón Peredo 2016). They are not definitive, incontestable solutions. As we said, the variables have been chosen subjectively but are quantifiable.

Consistent with the above, in our methodological proposal, we aim to present an individualised and coherent data structure. From this data, we will create a ‘third order’ of interpretive images (Montero Ruiz et al. 1998).

We have chosen a classic case study, an obligatory reference in Late Peninsular Prehistory synthesis literature which has been visited by multiple researchers throughout the twentieth century and which brings together, on the same panels, engraved and painted icons. The most significant ones contain both techniques of expression. This is the main challenge of the study. The combined use of radiometric

and geometric techniques to obtain metric documents lets us analyse this graphic narrative from quantifiable variables.

Regarding radiometric exploration, we will demonstrate the suitability of using a hyperspectral sensor with a working band between 350 and 1050 nm. With it, we have isolated several phases of pigment additions from subtly differentiated spectral signatures.

The geometric exploration of the rock surface is aimed at distinguishing between natural roughness and engraving grooves traced by the human hand. This implies an adequate data capture, i.e. accurate and high resolution, and processing of these data that differentiates between a natural or artificial origin of the micro-reliefs. To achieve this goal, we will rely on graphic solutions outside the visual experience (hidden geometries, search for edges, discrete curvatures etc.) and others within the visual experience (light and shadow maps), which are more intuitive but difficult to quantify.

Case study: Peña Tu's rock (Puertas de Vidiago, Asturias, Spain)

Peña Tu is in the north of Spain, in the central longitudes of the Cantabrian Region, at the eastern end of the region of Asturias. It is a prominent, isolated rock at the end of one of the Sierras Planas de Llanes, erosive witnesses of ancient levels of marine terraces, carved on quartzite and sandstone from the Cambrian and Ordovician periods, also affected by phylogenetic tectonic movements, and which define two altitudinal levels, around 150 m and 220 m amsl (Domínguez-Cuesta et al. 2019; López-Fernández et al. 2020).

The *Sierras Planas* form a plateau between the Bay of Biscay, 1.6 km to the north, and the mountain barrier of the *Sierra de Cuera*, 4 km to the south, which, in this longitude, reaches altitudes above 1100 m asl. All these mountainous features, running parallel to the coast, are the prelude to the huge massif of the *Picos de Europa*, with several peaks above 2600 m. This rugged terrain forms a narrow coastal communication corridor intensely inhabited by humans during prehistoric times. It is one area with the highest density of archaeological sites in the Cantabrian region (Fano Martínez 1998: 13) (Fig. 2).

The rock or 'Peña' is a residual outcrop of the quartz arenites and white sandstones of the 'Barrios' formation, which form these flat mountain ranges (Gutiérrez-Alonso et al. 2007). It has a height on its southern side (the most prominent, in favour of the slope of the hillside) of about 10 m. The opposite side, to the north, is only 5.8 m above the ground. Between the two opposing sides, there is an average thickness of about 4.8 m. It is on the eastern side of this thickness where the decorated panel is located (Figs. 3 and 4). The rock has an east-west length of 7.8 m.

Peña Tu was identified in the summer of 1913 By Eduardo Hernández Pacheco, the Count of Vega del Sella y Juan Cabré, and published by its discoverers the following year, once a first tracing of the set was composed in the autumn of that year 1913 (Hernández-Pacheco et al. 1914) (Fig. 5a). This was done freehand. It describes all the major elements that frame the formal and chronological discussions on the decorated panel throughout the twentieth century and the beginning of the 21st. That is, the authors describe (A) a larger anthropomorphic figure, engraved and painted with ochre strokes, slightly more than one metre high and about 60 cm wide, arranged at the extreme right of the panel (to the north); (B) the representation of a weapon arranged vertically next to it on the left, also engraved and with remains of paint; and (C) various depictions painted in red, always to the left of the larger anthropomorphic representation, among which we can distinguish groups of anthropomorphs of a classical schematic convention, series of points distributed in a nuclear and linear way, and other signs difficult to interpret due to their state of conservation. The entire decorated panel spans an area of just over 4 m wide and 1.3 m high.

Only certain icons carved on the wall using a picketing technique are omitted in the tracing, probably because, considering the authors, these motifs were recent; they should not be part of the archaeological analysis.

In that publication, the tracing is printed on a fold-out sheet in two inks (Red and black), which refer to the two techniques used in the graphic narrative (painting and engraving). There is no graphic reference to ridges of the rock support. A graphic scale was also not drawn, although a numerical fraction scale of 1:8 is indicated. There is no reference to the horizontal level of the composition. As we say, etched grooves are rendered in black with different thicknesses, using a shading convention. The painted areas are shown in red ink with different intensities, thus suggesting different conservation and sharpness of the icons. This early 20th-century tracing was the canonical image of the site for over six decades until the review was published in the 1980s.

With a different scientific paradigm and renewed reproduction techniques, a team led by P. Bueno and M. Fernández Miranda carried out a new tracing of the panel in 1981 (Bueno and Fernández-Miranda 1981). In this case, it was done using cellophane in direct contact with the rocky surface. Unfortunately, the graphic work of these authors was largely ruined by the faulty edition of the book in which it was published. The lack of tinting of the sheets on which the tracing was shown made most icons illegible (Fig. 6). For this reason, the narrative of the decoration of the panels can only be followed from the descriptions in the text, which are themselves extensive and detailed.

One author of this review, Primitiva Bueno, researched the site again twenty-six years later. It is the last major revision of the panel and was published as a diachronic context

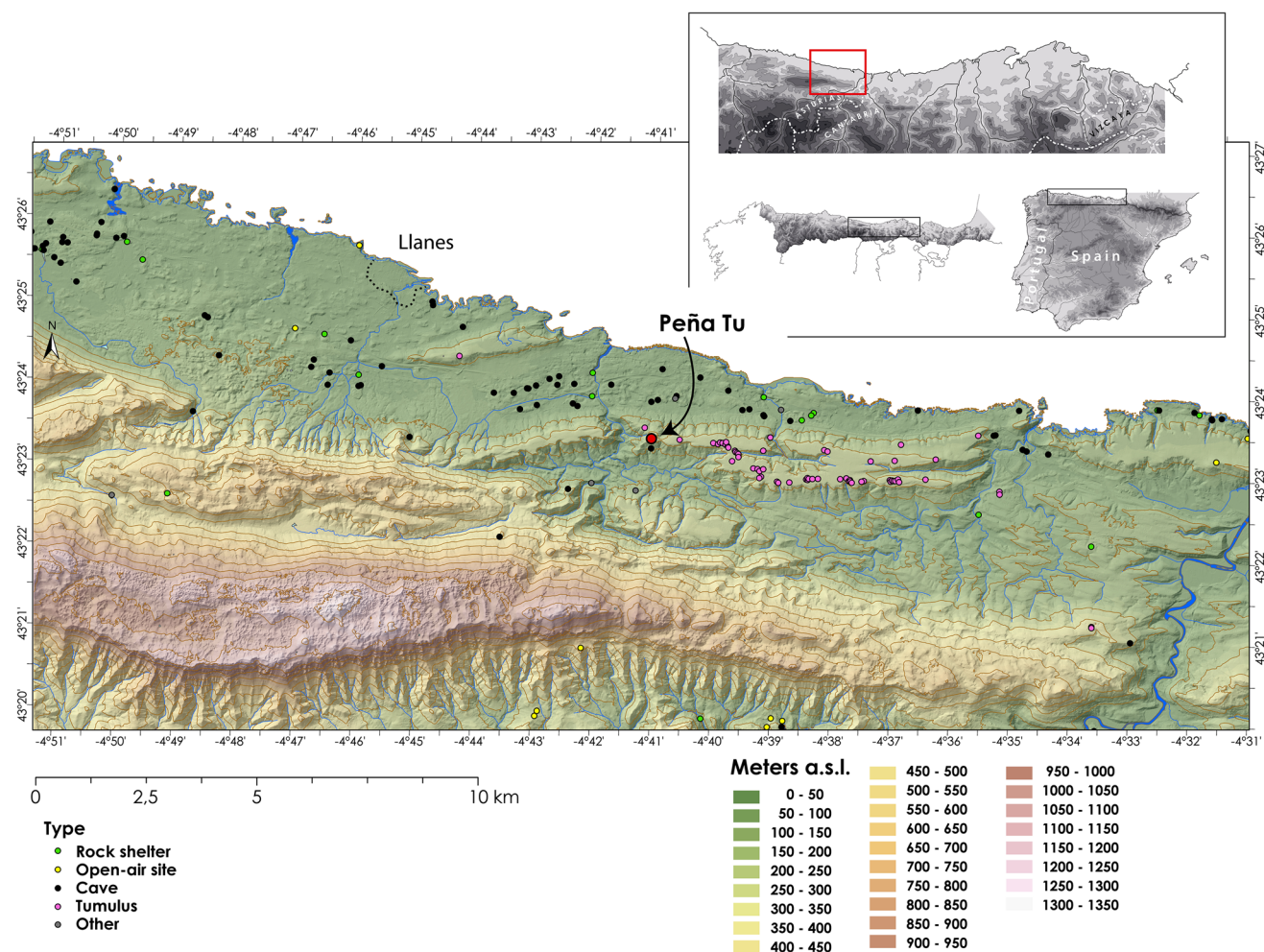


Fig. 2 Location of Peña Tu and other nearby prehistoric sites



Fig. 3 View of the Peña Tu site from the east in the evening of one of the documentation days. The pre-coastal mountain ranges around Llanes can be seen in the background

for the discovery of human remains in the nearby Fuentenegro cave (Barroso Bermejo et al. 2007) (Fig. 5b). In this case, the authors tell us that for the elaboration of their tracing, they have not resorted to methods that imply contact with the surface, but rather that they have used more sophisticated photographic techniques. This change in technical strategy brought with it some notable variations to the interpretation of the icons, as we will see in the ‘Discussion: critical and comparative analysis of data and interpretations’ section.

On this occasion, the tracing incorporates graphic ‘shading’ conventions that try to represent the natural roughness of the rock support and the pecked areas that represent recent cruciforms. Neither of these related aspects of the feature was discussed in the 1914 tracing. Nevertheless, the same graphic convention is used for the grooves delineating the greater anthropomorphic figure and the weapon. The icons and areas with pigment are represented in red ink with

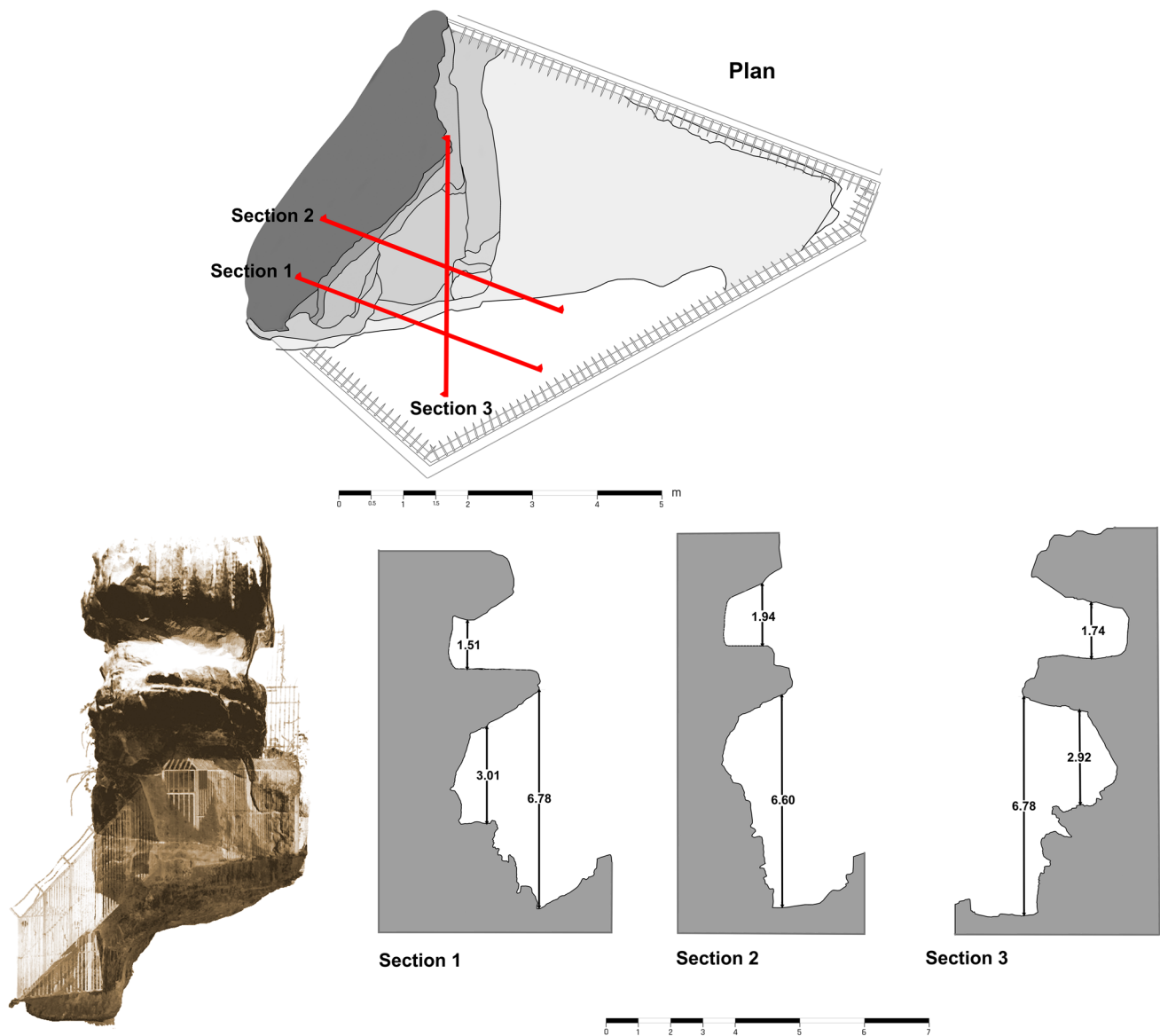


Fig. 4 Plan and elevations of the decorated rock of Peña Tu

slight variations in intensity, which appear to represent different degrees of preservation of the original lines.

From a different viewpoint, three years later, M.A. de Blas published a new interpretation of the site (Blas Cortina 2010). This author invites us to consider, with reference to the symbolic meaning of Peña Tu, not only the surfaces decorated with paintings and engravings but also the rock support itself: It is a stone volume with a supposed zoomorphic appearance. The work does not discuss in detail the appearance of the panel icons, nor does it reproduce a complete view of them. However, it does expand on the description of the weapon arranged next to the main anthropomorphic figure using graphics and text,

which is interesting considering our methodological purpose. In addition to this icon, he also reproduces a tracing of one of the small-sized anthropomorphic figures painted in red, the interpretation of which has interested researchers the most throughout the last century (Fig. 7). In none of the cases is any detail of the methodology followed for the elaboration of the tracings specified. However, his peculiar interpretation of both figures will help us show; in the ‘[Discussion: critical and comparative analysis of data and interpretations](#)’ section, the abundance and variety of explanations Peña Tu has offered throughout the history of the investigation.



Fig. 5 Comparative image of the Peña Tu tracings published in 1914 (a) and 2007 (b). In the case of the 1014 tracing, as it only has a numerical scale (1:8), the print size of the original figure has been checked to be able to reproduce the two tracings at the same scale

Technical scenario and methodology: approach of a dual strategy for the documentation of the archaeological site

The study of the painting and engraving techniques seen at the site involves two documentation strategies. The first, concerning the identification of pigment groups, is based on specialised electromagnetic spectrum sensors. The second, which defines the geometric reality of the engravings and the natural rock support, uses photogrammetry and laser scanning techniques.

Both strategies are carried out concurrently in the field, but their joint and complementary analysis is only possible through accurate georeferencing.

The prehistoric graphic expression needs comprehensive georeferencing to guarantee spatial coherence of the data in a time series, which can then be acquired to review its condition.

Every measurement has an error: No measurement is ever exact and must be rigorously adjusted, with the results undergoing statistical analysis. In geomatics, integrating global navigation satellite systems (GNSS), topographic total station (TTS), 3D terrestrial laser scanner (3D TLS), digital metric cameras and hyperspectral imaging systems all allow an accurate, reliable and rapid recording of information (Bayarri et al. 2021a, 2023). This information can be integrated into a geographic information system (GIS), which can be used extensively for research, management or decision-making (Bayarri et al. 2019; Ontañón et al. 2014).

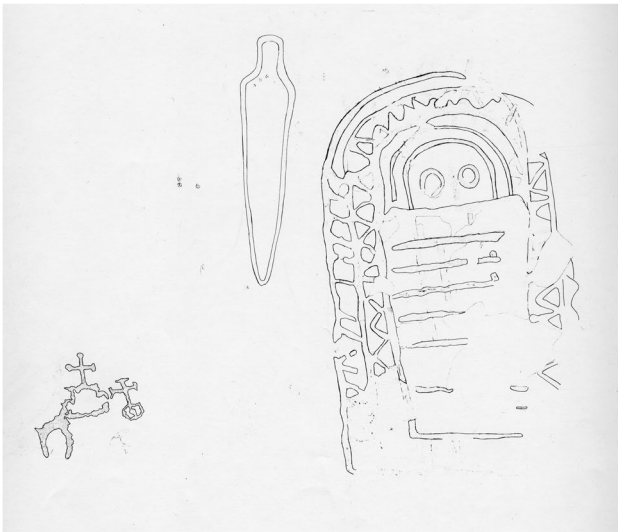


Fig. 6 Partial image of the tracing of El Peñatu after (Bueno and Fernández-Miranda 1981)

Integrating 3DTLS and GNSS allows a rapid, accurate and reliable recording of complex features such as the caves or cavities (Bayarri and Castillo 2009). It plays a pivotal role in the successful hybridization of results obtained through the integration of methodologies such as 3DTLS, GNSS and photogrammetry (Bayarri 2020). The accurate alignment of spatial data is essential for combining information derived from these diverse sources seamlessly. In data collection, the 3DTLS captures high-resolution point cloud data, providing detailed and accurate (up to 1–2 mm in phased-based systems for high reflectances) geometric information of the surveyed area. Simultaneously, GNSS ensures accurate positioning by leveraging satellite signals, offering global coverage for geolocation with an accuracy of around a few centimetres. Photogrammetry complements these techniques by using images to reconstruct three-dimensional scenes. The 3DTLS is adjusted within a free network linked to GNSS coordinates, allowing for the propagation of errors (Bayarri et al. 2021a). This interconnected system makes sure the laser scanner's measurements are aligned with accurate geographical references, enhancing the reliability and spatial coherence of the hybridised results. The ground control points (GCP) of photogrammetry are obtained from the adjusted 3DTLS point cloud, reaching a few millimetres of accuracy in their determination.

Hyperspectral imaging is typically acquired through scanning by using a rotary scanner. To effectively use these datasets alongside with spatial data, there is often a need to make a registration or georeferencing process to set a specific map coordinate system, in our case European

Terrestrial Reference System 1989 (ETRS89). An essential step involves determining the precise position from which hyperspectral images were captured. This is achieved through the registration of GCP, which serve as reference markers in both the 3D model and the hyperspectral imagery. By aligning these control points, it is possible to establish the spatial relationship between the two datasets, helping with an accurate fusion of hyperspectral information into the three-dimensional model. This process not only enhances the spatial context of the hyperspectral data but also enables the reprojection of 2D hyperspectral information onto the 3D model's surface. Integrating hyperspectral and 3D spatial data offers a holistic understanding of the rock art site, allowing for in-depth analysis of material composition, pigment distribution and hidden details.

The fusion of hyperspectral imaging with photogrammetry yields several useful outcomes. First, the union provides an enriched spatial context by integrating hyperspectral data with a 3D model. This synergy empowers researchers to better interpret the complex relationship between materials and the surface of rock art. Second, this combination enhances material discrimination capabilities, enabling the precise identification of pigments, binders and other materials used to make rock art. Third, the integration offers a holistic approach to analysis, leveraging the strengths of both techniques. Finally, the comprehensive dataset obtained could aid in developing effective preservation and conservation plans. It helps identify areas of deterioration, understands material vulnerabilities and guides targeted conservation efforts, thus helping with the long-term preservation of these culturally significant artworks.

Image registration serves as the initial phase, aligning hyperspectral and photogrammetric datasets for spatial coherence by correlating corresponding points between the two sets of images. Following registration, the integration stage combines the datasets, merging hyperspectral and photogrammetric data into a cohesive whole. This integration involves overlaying hyperspectral information onto the 3D model, associating spectral data with precise spatial coordinates. Then, a comprehensive analysis of the integrated dataset ensues, exploring the hyperspectral information within the 3D model. This in-depth examination allows for the identification of materials, pigments and subtle features present on the rock art surface, establishing correlations between spectral signatures and specific areas. Finally, the interpreted findings are contextualised within an archaeological framework. The integrated dataset enables a more nuanced understanding of rock art, aiding in pigment identification, unveiling concealed details and unveiling patterns that might remain obscured when using individual techniques in isolation.

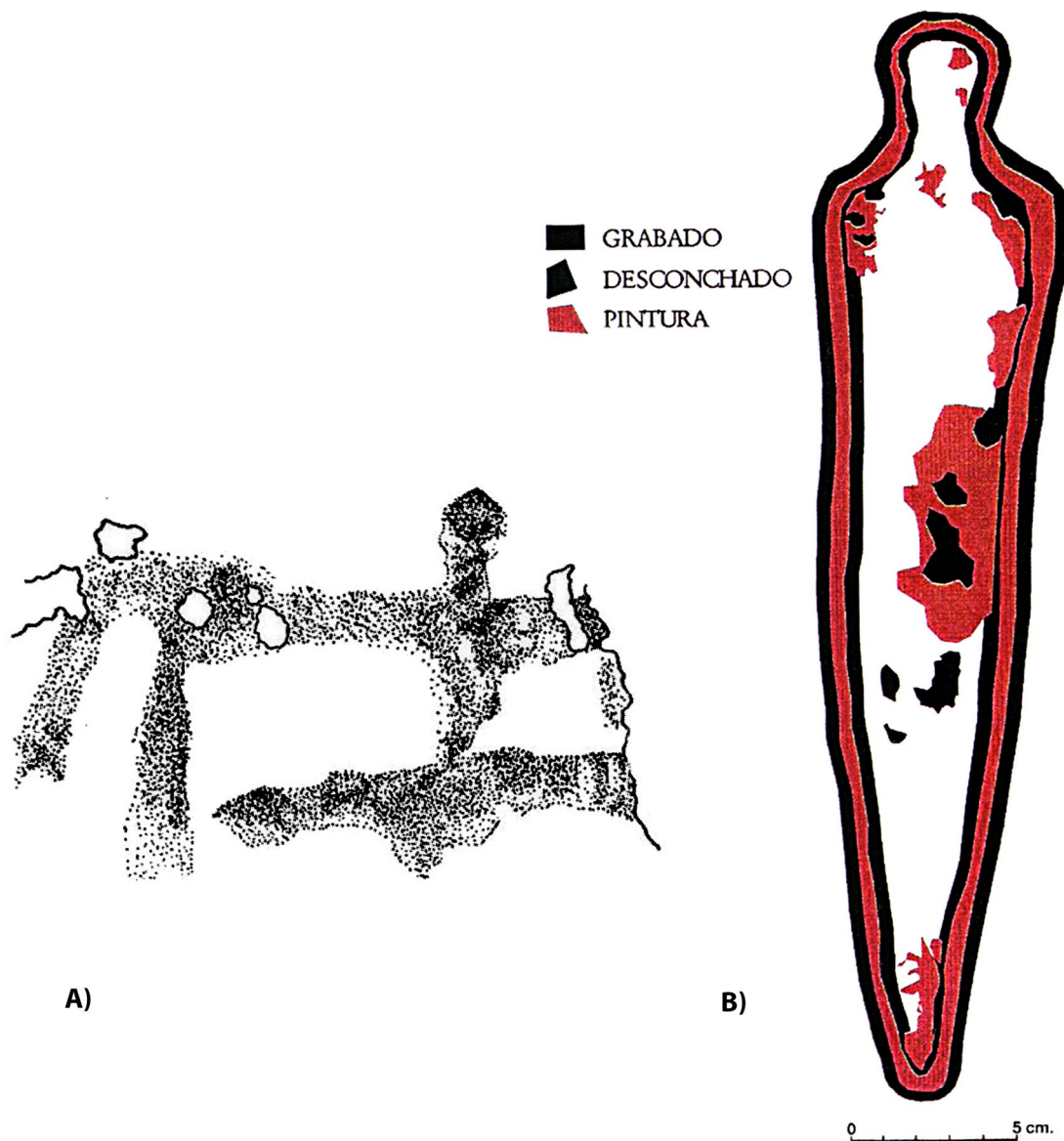


Fig. 7 Representation of the anthropomorphic figure with crozier (A) and the weapon (B) of Peña Tu after Blas Cortina (2010)

Hyperspectral documentation of the rock art panel

Hyperspectral imaging is a powerful technology that has found applications in various fields, including rock art studies. It refers to the acquisition and analysis of images captured at multiple wavelengths in a region of the electromagnetic spectrum. The significance of hyperspectral imaging in rock art studies lies in its ability to reveal details and information that may be invisible or difficult to discern with the naked eye or traditional imaging methods. Unlike conventional photography or even multispectral imaging, which captures images at

a few wavelengths, hyperspectral imaging records data across a continuous and wide range of wavelengths, often spanning the visible and near-infrared regions of the spectrum.

This spectral range lets researchers analyse the unique spectral signatures of different materials present in rock art, such as pigments, binders and underlying rock surfaces. By processing the reflectance or absorption patterns at various wavelengths, hyperspectral imaging can provide valuable insights into the composition, layering and even faded or obscured elements and contribute to analyse, interpret and preserve such valuable artwork.



Fig. 8 View of the Specim V10E spectrograph scanning the lower bench of the site

Hyperspectral sensor

The hyperspectral system used for the study was formed by a Specim V10E spectrograph (Spectral Imaging Ltd., Oulu, Finland) covering the spectral range of 400–1000 nm, an sCMOS camera (CL-30, effective resolution 1312×728 pixels by 12 bits), an objective lens (Cinegon 2.4/30 mm focal length) and a rotating scanner light and data acquisition (DAQ) spectral software (Fig. 8).

The bandwidth was reduced to 5.6 nm by applying binning to improve the signal-to-noise ratio to produce 214 spectral bands from each pixel to form a relatively continuous spectral curve.

The data were recorded as a hypercube with two-dimensional spatial images and wavelength bands as the third dimension. Two hundred fourteen spectral bands were extracted from each pixel to form a relatively continuous spectral curve.

Illumination sources

Data was recorded in two ways. The first used natural direct sunshine incident light, and the second used a Philips Photolita Lamp Bulb 240 V 500 W. The spectral signature of the lights was obtained from the 1 nm wide narrowband FieldSpec Pro FR spectroradiometer made by analytical spectral devices, measuring spectra over a range of 350–1050 nm (Fig. 9).

Pre-processing: reflectance calibration (Fig. 10)

During the field campaign, apart from taking the hyperspectral data, a white target using the light set-up and a black image by closing the camera's shutter were measured.

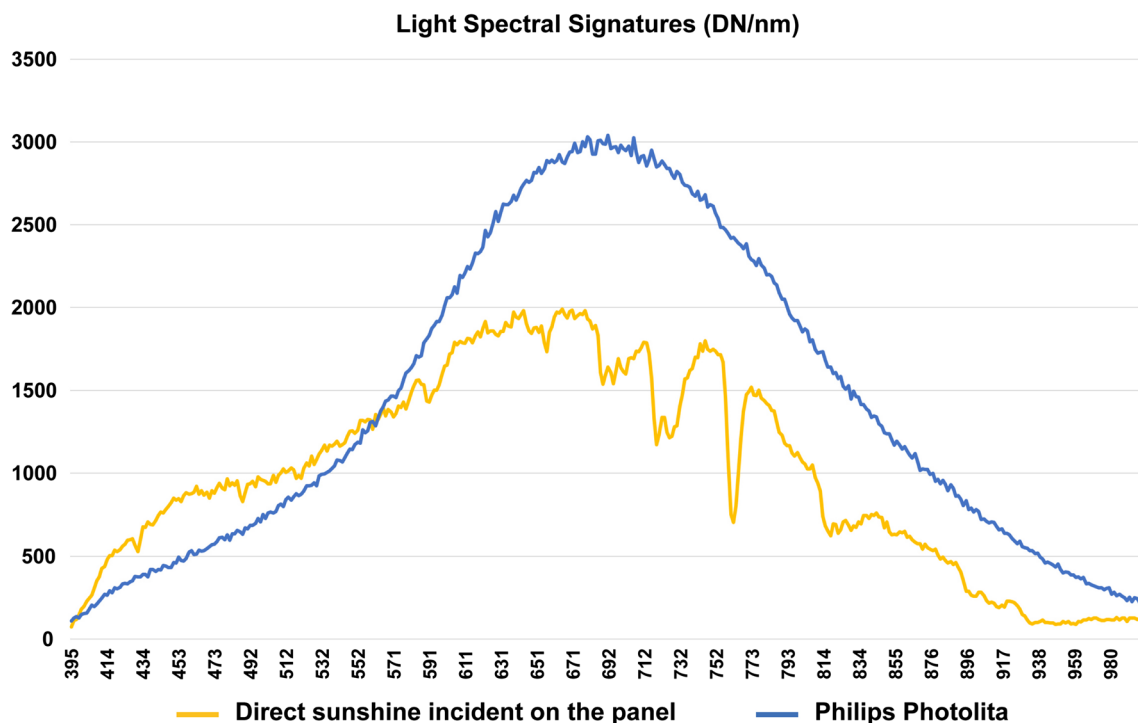


Fig. 9 Spectral signatures of lights at working distance. The vertical axis represents the relative spectral power measured, and the horizontal axis is the wavelength in nanometres where it was measured

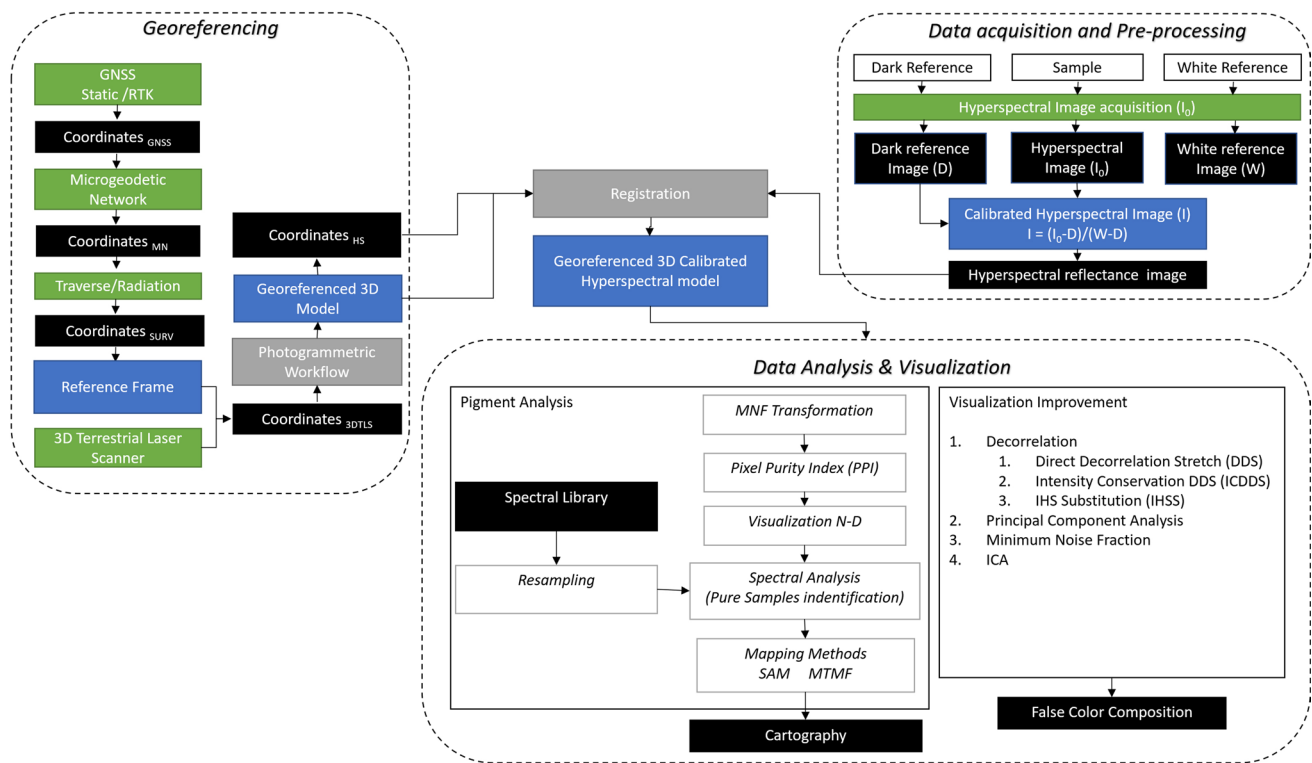


Fig. 10 General WorkFlow, adapted from Bayarri (2020) and Bayarri et al. (2019, 2021a, b)

These measurements were taken to eliminate the effects of black (B) and white (W) backgrounds on the hyperspectral images. The calibrated reflectance values (R) of raw sample images (I) were calculated by the following formula:

$$R_i = \frac{I_i - B_i}{W_i - B_i}$$

where i is the pixel index.

Processing: geometric correction

This process aims to eliminate errors or distortions of the image to adapt the image to an established 3D reference system that enables comparison.

The steps to follow in the geometric correction of an image are

- control points selection,
- transformation calculation,
- image resampling, and
- process verification.

Here, the correction was made by projecting the hyperspectral image onto the 3D model obtained by photogrammetry, which was subsequently re-projected following an orthogonal

plane. The hyperspectral imaging camera had certain limitations regarding the imaging range and resolution. The pixel size was set to 1 mm, and each recording had about 1 m².

Pigment analysis

The results can be divided into two categories.

- Fully interpreted information: the end is to create a cartographic representation of pigment by classifying data.
- Fully uninterpreted information: the end is to create false colour compositions to enhance paintings hardly appreciated by the naked eye.

Minimum noise fraction transformation Original data had 214 spectral bands; the minimum noise fraction (MNF) transformation determines the dimensionality of the image by separating the noise from the image (Green et al. 1988). It produces orthogonal bands ordered by their information content.

Pixel purity index The pixel purity index (PPI) aims to locate the purest spectral points of the hyperspectral image. The method is based on the assumption that the most extreme

points in the scatter plots are the best candidates to be used as end members. This model offers satisfactory results when the components residing at a sub-pixel level seem spatially separated (Boardman and Kruse 1994).

n-D display This locates, identifies and groups the purest pixels and the most extreme spectral responses in a data set. The n-D viewer helps to visualise the shape of a data cloud resulting from the plotting of image data in spectral space (with image bands as raster axes). The maximum number of bands to be displayed is 54.

Unsupervised ISODATA (iterative self-organising data analysis technique) classification The unsupervised classification methods consist of the search for natural groupings of pixels (clusters) in the spectral space defined by the p variables (spectral bands), with no auxiliary information from the analyst, i.e. no learning samples are used.

A new adaptation of the ISODATA (iterative self-organising data analysis technique) method has been applied, according to Bilius and Pentiu (2020). Parallel factor analysis (Parafac) is a method to decompose multi-way data and analyse the data using non-supervised classification tools. It is an iterative method repeated until some convergence is reached; it is self-organising in locating clusters from minimal initial data.

Visualisation improvement

It consists of applying specific techniques to enhance and group pigments that are difficult to see with the naked eye.

Decorrelation adjustment Decorrelation adjustment is implemented for generic binary band data stored in 16 bits, as described by Sabins (1986), and is used to enhance the image. It consists of converting the data to the space defined by the main components of the original bands, followed by equalising the data according to the new axes, and finally converting the data to the initial space and combining the bands with the primary colours, red/green/blue (RGB). In this way, the dots are more evenly distributed in the RGB space so that the image will show much higher contrast.

Principal component analysis Two principal component algorithms were used, one adapted from Richards (1986) and the Karhunen–Loeve transformation, as described by Loeve (1978), which were programmed in the IDL language. Both methods were carried out using correlation matrices, and all bands were included in the transformation.

Minimum noise fraction transformation The minimum noise fraction (MNF) transformation was implemented as described by Green et al. (1988). It was created to enhance

the ability of principal component analysis (PCA) in separating signal and noise components in multispectral images. Unlike PCA, MNF maximises each component's noise content instead of the data's variance, resulting in a higher signal-to-noise ratio when reversed. The MNF transformation effectively removes noise from the image, determining its actual size and reducing computational requirements. This linear transformation involves two separate rotations using the main components of the noise covariance matrix to decorrelate and rescale noise in the data and then using the main components from the original image data after the noise has been whitened and rescaled. The final eigenvalues and associated images determine the inherent dimensionality of the data for subsequent spectral processing.

Independent component analysis Independent component analysis (ICA) can be used in multispectral datasets to transform a set of randomly mixed signals into mutually independent components, according to Hyvarinen (1998, 1999).

These transformation analyses are used for deriving a set of low-dimensional features from a larger group of variables. However, another application is to visualise higher dimensional data and clustering, one of the key data mining methods for discovering knowledge in multivariate data sets. The goal is to identify groups (i.e. similar coverages) of similar objects within a data set of interest.

Geometric and textural characterisation of the rock support and the engravings

Photogrammetry

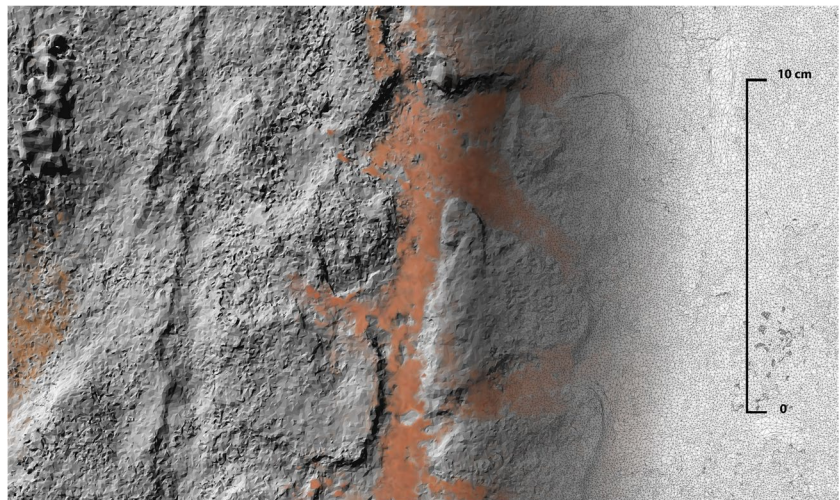
To create the 3D model, a Sony ILCE 7 S Mark ii was used, with a 35 mm Sony Distagon T* FE 35 mm f/1.4 ZA previously calibrated. The mean flying altitude was 45 cm, and the ground resolution was around 100 microns (Fig. 11). The coverage area was 5 m², and ten GCP taken from the 3DTLS data scanned targets were used with a mean error of 0.43 cm.

Stereoscopic coverage has been ensured over the entire area. In the flight to obtain the 3D model, the overlap in the longitudinal direction reached 80%, and the transversal overlap varied according to the coincidence of the axes of the flight (Fig. 12).

Illumination source

An LED Ring CNR-332 with a colour rendering index (CRI) of 95% was used to ensure the faithful reproduction of the colour of the rock art panel. The illuminance is 1900 lx/1 m, dimmable from 3 to 100% and was spectrally calibrated (Fig. 13).

Fig. 11 Density of triangles in the photogrammetric model



Processing

In this stage, the photogrammetric shots are aligned as described by Bayarri et al. (2015). Traditional digital methods were executed in VisualSFM (<http://ccwu.me/vsfm/>).

During the data capture stage, a control process was applied to the incident light to ensure colour management, keeping the colour and its perception constant across all the relevant processes. A Datacolor SpyderCHECKR colour chart was used to record colour (Fig. 14).

The colour management was based on the consensus achieved through the International Color Consortium (ICC), which focuses on the following:

- Using colour profiles to describe colour transformations. The colour profile is characterised by gamut, dynamic range and tonal reproduction.



Fig. 12 View of the main panel with the photogrammetry equipment

- The profile connection space (PCS) is a strategy for the transformation of colour between an input and output space.
- The colour management module is a colour transformation tool that feeds on colour profile information.

The radiometry of the processed images has made effective use of all the bits according to each case, avoiding the appearance of empty digital levels in the case of the 12-bit image.

Analysis strategy and visualisation

A 3D model is several points in space connected by complex geometric entities (i.e. vertex, edges, triangles, curved surfaces etc.) with a texture assigned. Textures consist of overlaying a two-dimensional colour-calibrated image on the surface of the 3D model.

The result of the photogrammetric model has been a 3D model with 12 million polygons and four textures with 8192×8192 size (Fig. 15). Three projection planes have been applied to the generated model to have as orthogonal a projection of the elements as possible (Figs. 19 and 20).

In addition to the 3D model, a georeferenced orthoimage with 100-micron pixel size and a digital elevation model (DEM) has been generated as a basis for further studies.

As we have indicated in the 'Introduction' section, we can group the different ways of visualising these 3D geometric models into two groups:

- a) graphical solutions within the visual experience
- b) graphical solutions outside the visual experience

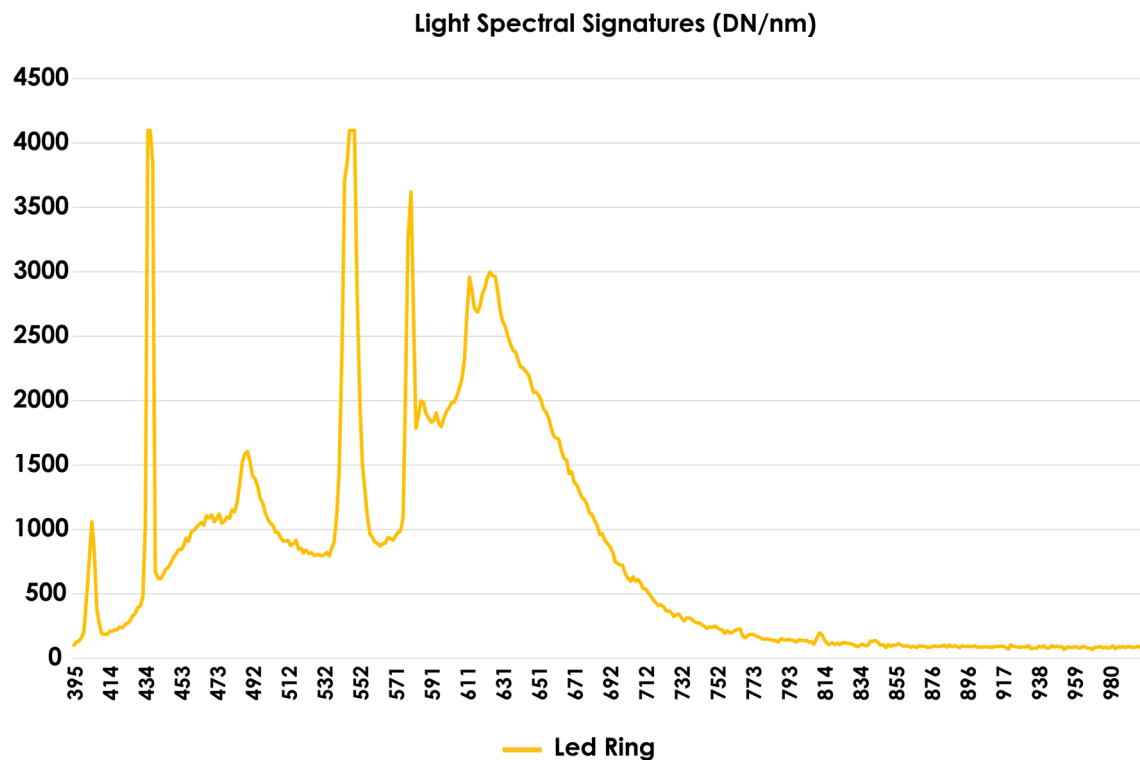


Fig. 13 Spectral signature of light at working distance. The vertical axis represents the relative spectral power measured, and the horizontal axis is the wavelength in nanometres where it was measured

Graphic solutions within the visual experience These are solutions that deal with our understanding of three-dimensional space from an ‘appearance of volume’. Most of the time, this space materialises in maps of light and shadow. Originally, the hillshade represented shadows and solar radiance levels on the ground. Using Digital 3D, models can be simulated by locating a spotlight or sun in a specific place, which allows us to create a sensation of depth with shadows projected on the model (Fig. 16). They generally improve the visual quality of the 3D model by assigning clarity values to each triangle of the model according to the angle of incidence of the simulated spotlight or sun. So, these maps allow the adjustment of light, opacity, reflectivity, shading and other parameters. This process also allows the derivation

of products such as polynomial texture mapping, also known as reflectance transformation imaging (Mudge et al. 2006), for interactive visualisation of objects under different lighting conditions to reveal surface phenomena.

Graphic solutions outside the visual experience These graphical solutions let us isolate or analyse certain geometric features of the 3D model and express them in maps of arbitrary scalar values. Such maps are independent of the observer’s viewpoint or their understanding of space. They are accurate metric documents, interchangeable between observers. In fact, both types of solutions complement each other and are often used in the same document.

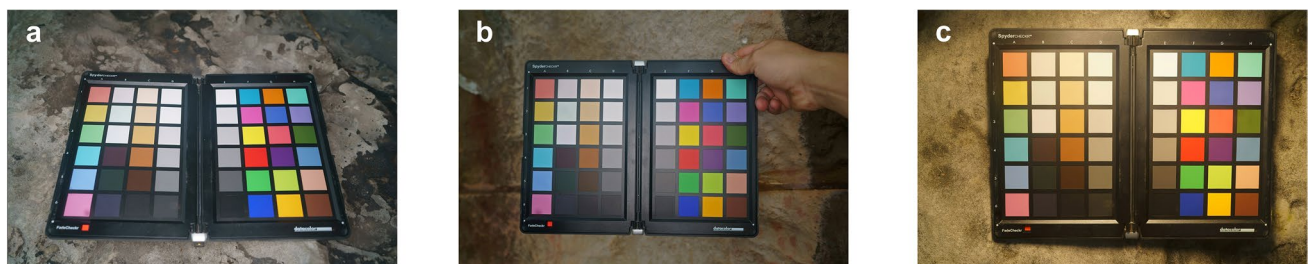


Fig. 14 Three measurements of light with Datacolor SpyderCHECKR colour chart: (a) natural incident light, (b) frontal LED ring light, and (c) Philips Photolita lamp



Fig. 15 Frontal (a), isometric (b) and lateral (c) projection of the main panel based on the photogrammetric model

In our analysis, we have used these two filters.

- Curvature map of measured data: curvature is the amount by which a geometric object deviates from being flat (Nielsen 2020). The maximum curvature value at each polygon vertex has been calculated and represented.
- Angle differences between each normal of a polygon vertex and a reference direction normal to the panel (Figs. 17 and 18).

Projection planes selection

A set of 3 points for each working area has been selected to define precisely each projection plane.

The zones have been divided (Figs. 13 and 14):

- anthropomorphic and weapon
 - The main anthropomorphic figure and the weapon next to it are engraved on the far right-hand side of the decorated

wall. Its ‘median plane’ is slightly oblique to the median major plane of the rest of the decorated panel on its upper bench. It is a subplane oriented towards the outside of the rock. It is appropriate to apply its own projection to it.

- upper bench

This is an overhanging rocky bench bordered, at its base, by a natural sub-horizontal crack. It is a surface of 3.4×1.9 m, more or less homogeneous on its face side, so it is appropriate to establish a single median projection plane. However, the right end of the surface moves progressively away from this plane of projection, so the outer limit of the larger anthropomorphic figure is slightly distorted (Fig. 19).

- lower bench

Unlike the upper bench, with which it borders, the face side of this bench has a homogeneous ‘positive’ or convex inclination and a general pseudo-vertical dip, which allows for a projection onto a common plane without notable distortions (Fig. 20).

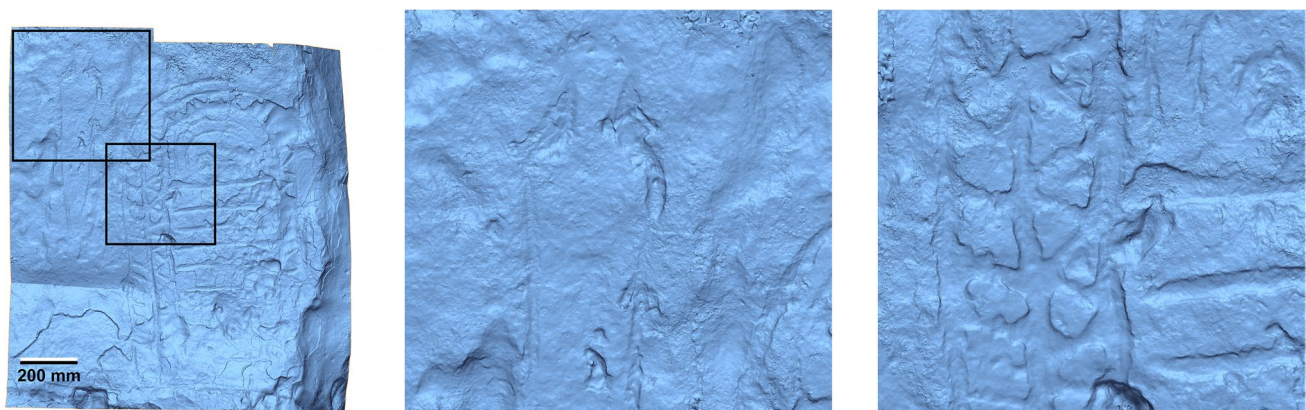


Fig. 16 3D hillshaded model of the panel

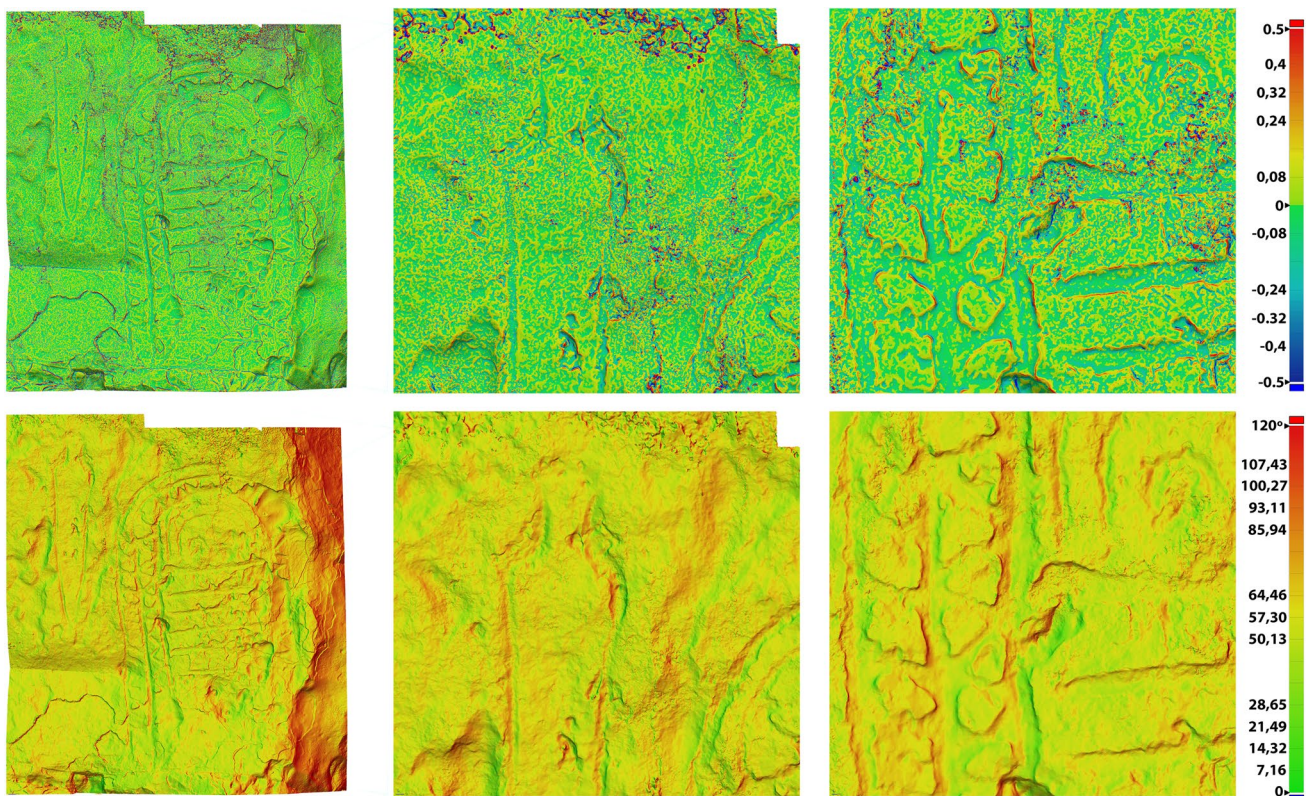


Fig. 17 Top: curvature map of measured data. Bottom: angle differences between each normal of a polygon vertex and the normal to the panel

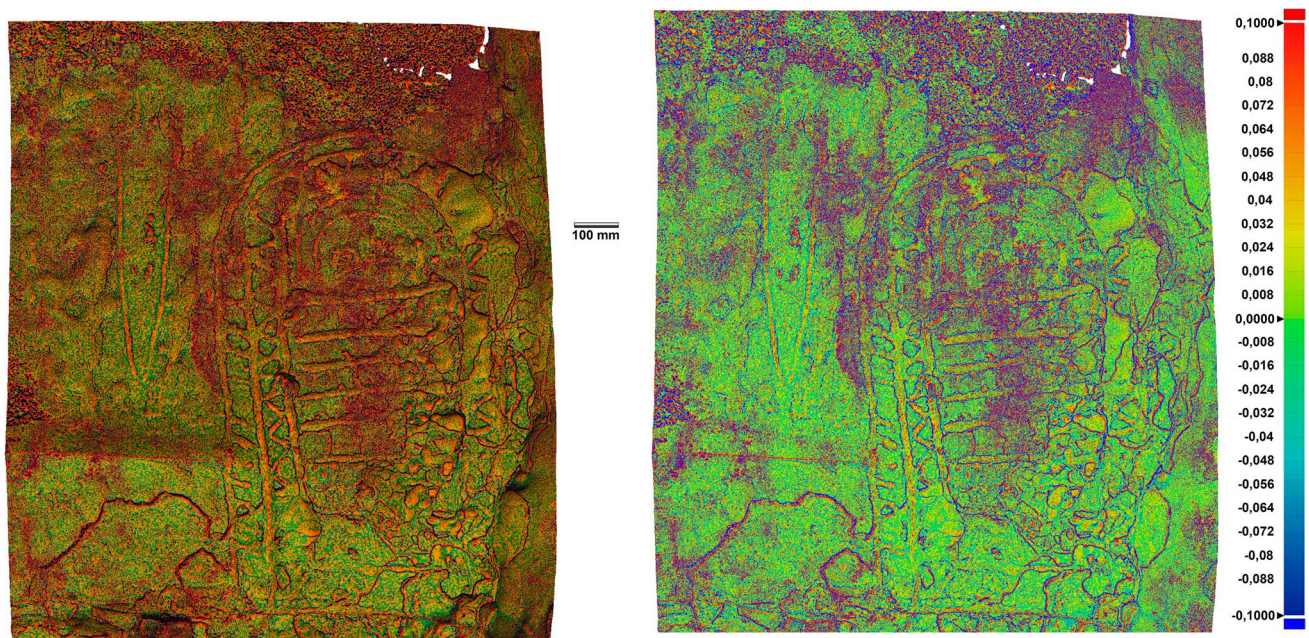


Fig. 18 Example of a combination of a hillshaded map and a curvature analysis (left) versus the curvature map alone (right)

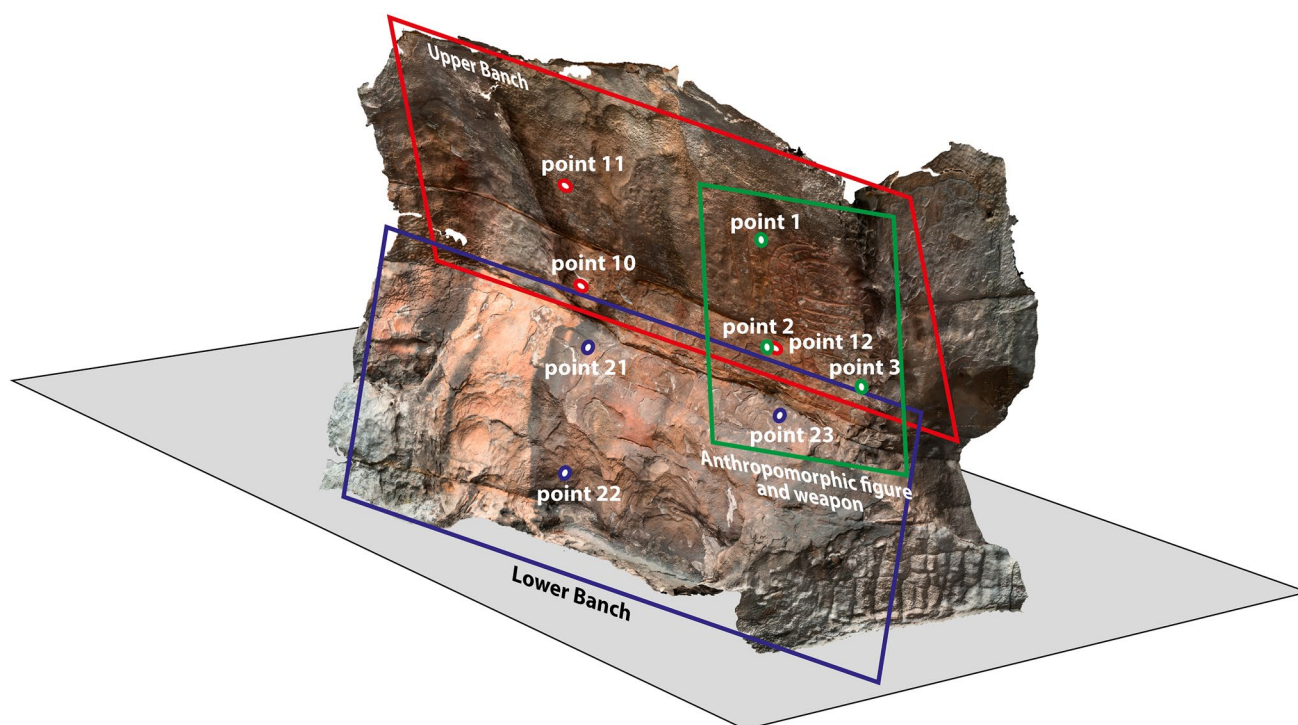


Fig. 19 View of the projection planes with the location of the points that defined these planes

Parallelism of radiometric spectra in geometric models

The surface represented in the hyperspectral images results from a conical projection that suffers anomalies or deformations regarding the position it should actually occupy in comparison with the true orthoimage obtained from integrating the 3D laser scanner and terrestrial photogrammetry. The geometric corrections are intended to reduce these errors, so the resulting image after these processes keeps, as far as possible, the radiometric values of the initial image and adapts to a chosen reference.

In this case, the process of taking an image as a reference is known as registration.

Basically, the two main reasons for geometrically correcting an image are to eliminate errors or distortions and to adapt the image to a reference system, allowing it to be compared with other elements in the same projection.

Geometric corrections refer to any change in the position of pixels in an image. The changes can be explained by a numerical transformation, the expression of which may be

$$F1(x, y) = G1(f, c)$$

$$F2(x, y) = G2(f, c)$$

where x and y refer to the coordinates of the corrected image, and f and c are the input image coordinates.

The sequence of phases in the geometric correction of an image is as follows.

1. Hyperspectral image acquisition: to obtain RAW data
2. Pre-processing: the result is the hyperspectral reflectance image.
3. Resampling of the image: to theoretically match the cell size in x and Y .
4. Calibration: obtaining reflectances (I) from raw data (I_0) by using dark (D) and white (W) references by using the expression $I = (I_0 - D) / (W - D)$
5. Georeferencing: to convert hyperspectral data into spatial data. The result is a georeferenced 3D-calibrated hyperspectral model. This model will be used for analysis and visualisation to create cartographies and false colour compositions. The stages are as follows:
6. selection of control points,
7. calculation of the transformation,
8. resampling of the image, and
9. verification of the process.

Here, the correction has been carried out by projecting the hyperspectral image onto the 3D model obtained by photogrammetry, which has been re-projected following an orthogonal plane (Fig. 21).

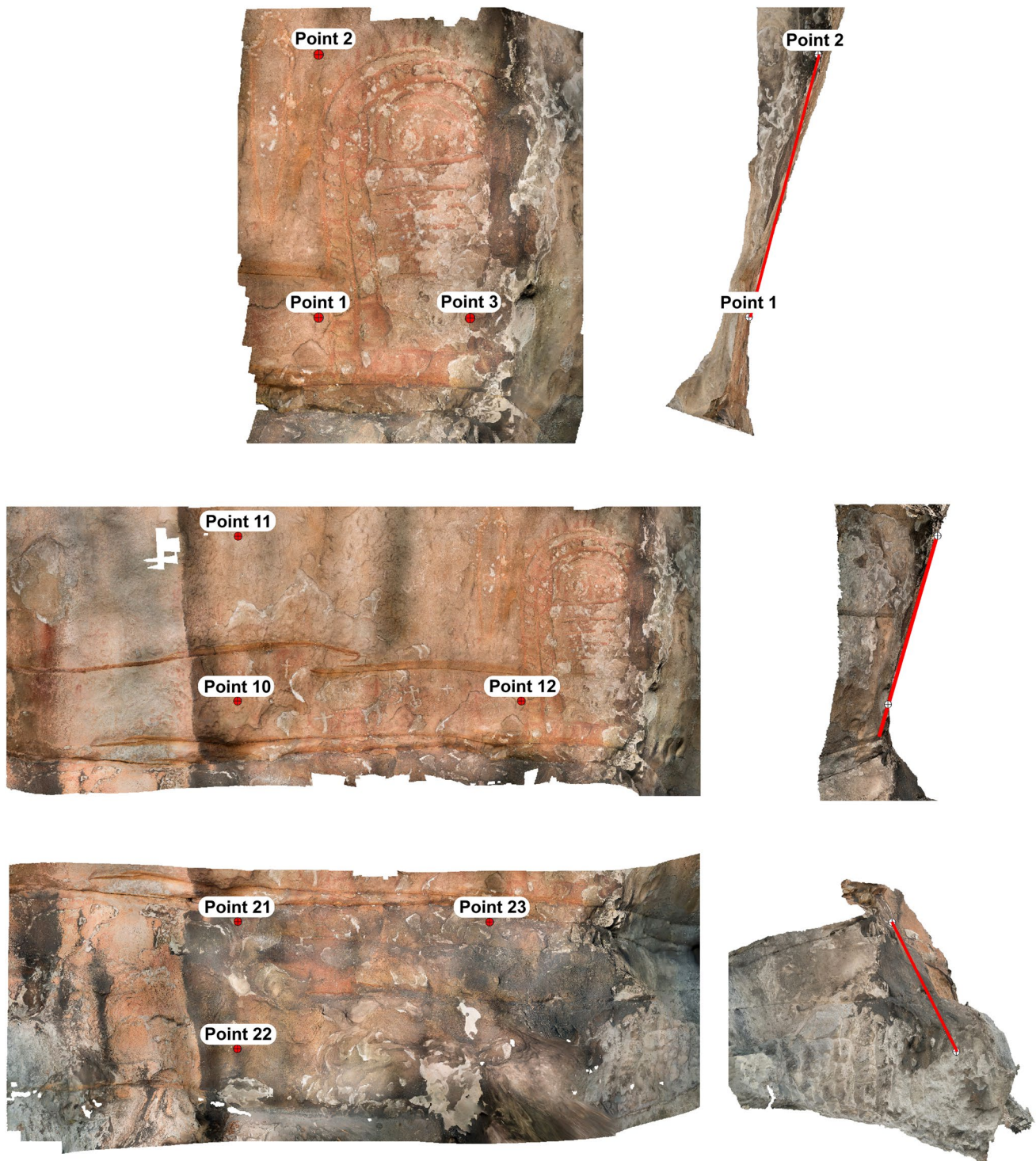


Fig. 20 Front and side views of the three projections used in all images. The position of the projection points is indicated

Visualising and analysing data derived from hyper-spectral imaging and photogrammetry in rock art studies requires the use of specialised software tools and algorithms. The typical steps and tools used for this purpose are as follows.

Photogrammetric 3D models can be generated using various photogrammetric software options such as Agisoft Metashape (Agisoft LLC., St. Petersburg, Russia), RealityCapture (Epic Games, Inc., Cary, NC, USA) or Visual SFM (Developer: Changchang Wu). These models are saved



Fig. 21 Parallax process between radiometric data and geometric models

in the Wavefront.obj file format, accompanied by several 8192×8192 images in JPEG, PNG or TIFF formats, in the function of the rock art's extension and the predetermined resolution. Visualisation of the 3D models can be done using tools like Blender (Blender Foundation, Amsterdam, the Netherlands), MeshLab (ISTI-CNR, Pisa-Rome, Italy) or Unity (Unity Software Inc., San Francisco, USA).

Hyperspectral remote-sensing data is stored in the BSQ generic binary format (.BSQ), and the algorithms produce data stored in the same format. Remote-sensing software such as ERDAS Imagine, Exelis ENVI or Fiji can be employed for data calibration and processing. Tools like Matplotlib in Python or specialised hyperspectral visualisation software contribute to the creation of informative visual representations. Only the outcomes of pigment analysis, namely Cartography and False Colour compositions, are stored in standard JPG or TIF formats indexed to the 3D model using GCP and the transformation method. A texture is then generated and indexed to the geometric model, and the results can be visualised with the same tools.

Orthorectification of 3D data can be performed to generate 2D representations, which can be managed using GIS software such as ArcGIS (Esri, California, USA), QGIS (QGIS Development Team) or GvSIG (Asociación gvSIG, Valencia, Spain).

Integrating hyperspectral and photogrammetric data often requires a multidisciplinary approach, involving collaboration among researchers in fields like remote sensing, archaeology and computer vision (Barrera et al. 2009). The selection of specific tools and algorithms is contingent on the research objectives, the features of the rock art site and the available resources.

Discussion: critical and comparative analysis of data and interpretations

Hyperspectral imaging is now a widely adopted tool in heritage studies and art history, used for the examination of paintings, objects, manuscripts, wall paintings etc. The diverse

pigments used, often derived from minerals in ancient artworks, are easily discernible through spectroscopy. Hyperspectral imaging proves valuable in mapping the distribution of pigments and inks, characterising them, identifying binders, recognising techniques, visualising overlaid sketches or figure outlines and studying palimpsests (Fischer and Kakoulli 2006; Le Mouélic et al. 2013; Daniel and Mounier 2015; Daniel et al. 2017; Mulholland et al. 2017; Daveri et al. 2018; Cucci et al. 2019; de Viguerie et al. 2020; Li et al. 2020).

In archaeology, hyperspectral imaging has been applied to investigate the polychromy of Greek sculpted friezes, Egyptian tombs and Roman baths (Alfeld et al. 2018, 2019; Cortea et al. 2021). Despite the advancements of hyperspectral imaging in heritage studies, its application in rock art archaeology is relatively new and remains largely uncommon (Bayarri et al. 2016; Bayarri et al. 2019, 2021a, b). This is generally associated with the challenges with the outdoor implementation of hyperspectral instruments. The conditions pose difficulties in obtaining images that adhere to the prerequisites of uniform illumination and the minimization of optical and geometrical distortions (Alexopoulou et al. 2021).

Integrating hyperspectral imaging and photogrammetry has emerged as a powerful and multifaceted approach, delivering significant contributions to archaeological research and enriching our understanding of diverse sites (Schmitt et al. 2023). This combined method proves instrumental in various parts of analysis, including the characterisation of pigment composition and artistic techniques. It helps with the discernment of faded or weathered elements, unveiling hidden motifs and layers that may be obscured. The integration enables the mapping of mineralogy and subsurface features, shedding light on the geological context of archaeological sites. Beyond the technical aspects, it contributes to a deeper understanding of cultural context and symbolism, unravelling layers of meaning embedded in the artefacts (Defrasne et al. 2023). Additionally, the documentation capabilities of this integrated approach play an important role in conservation efforts, providing detailed records for preservation

initiatives. Furthermore, it helps with chronological and stylistic analysis, offering a comprehensive toolkit for archaeologists to explore and interpret the intricate tapestry of human history encapsulated within archaeological remains.

In this paper, we will not detail the chrono-cultural implications of our reading of the panel from an archaeological viewpoint. As can be deduced from the previous sections, the contribution of this study is eminently theoretical and methodological. In other texts, we plan to develop these other interpretative questions. Still, from an eminently descriptive viewpoint, we will address the evidence that our method contributes to the archaeological discussions raised in Peña Tu because of the successive documentation of its icons throughout the twentieth century and the first decade of the twenty-first century. Above all, we will focus on certain ‘hot spots’ that have been described differently according to authors (or according to specific publications by these authors) or whose very existence has been denied. Although it may seem that a large part of our scientific effort merely discusses previous proposals, beyond these validation-refutation exercises, our documentation can detail original descriptions of the panel’s most important and ‘classic’ motifs and show the existence of decorated areas never previously considered. No less important are the possibilities that our method reveals in terms of detecting later additions of pigment and evaluating the state of conservation of the decorated ensemble.

General view

From the viewpoint of the panel as a whole, in terms of general proportions, we start from the disadvantage of lacking data on how the three major revisions of the site were projected onto the plane (Fig. 5). Whether a single projection plane was used or several. As the tracing techniques have also been threefold, freehand (Hernández-Pacheco et al. 1914), copying on a cellophane adhered to the rock (Bueno and Fernández-Miranda 1981) and photographic techniques (Barroso Bermejo et al. 2007), it is possible that, in some proposals, this question has not been considered. Nor do we have references to the horizontal plane to help us explain the inclination of any of the motifs or the angular relationship between motifs. Thus, in the 1914 proposal, the angular relationship between the larger anthropomorphic-sword duo and the rest of the representations to their left does not make sense in a common projection. In this proposal, there is also an error in the position of the motifs on the far left in the possible representation of a quadruped or quadrangular geometric figure. Clearly, this group on the far left has been placed in a lower position than in reality. These anomalies probably arise because the tracer, using a freehand technique, has worked from various positions, partially

reproducing the motifs and with little concern for angular rectifications of the whole.

In this sense, the 2007 reproduction is more accurate if we imagine a single projection plane. However, the long-width proportions of the larger anthropomorphic figure are striking, as well as the marked vertical asymmetry of the borders and arches that define its upper part. The authors of the publication consciously reproduce this last detail. They indicate that the motif has been adapted to the edge of the right end of the rocky plane, and for this reason, this area has been delineated in a more ‘ovoid’ shape than the arches on the left side (Barroso Bermejo et al. 2007: 134). We agree in part with this novel assessment, although not to the degree of deformation in their tracing. Although we have no data on the photographic techniques used, we can only imagine that optical aberrations in the lenses used to capture the data explain this marked deformation.

The major anthropomorphic figure

In addition to this disparity in the general proportions of each tracing, we have observed other differences in the internal decoration of this motif. It is difficult to extract the peculiarities of the engraved traces from the 2007 tracing since it uses a shading convention that is sometimes indistinguishable from other conventions dedicated to the natural roughness of the rock. But, the texts of all these publications hardly describe the details and scope of this technique. From our data, we can see that the engraved grooves delineate a shape enveloped by two larger borders down to the foot of the image. Here, only the inner border has horizontal continuity. In addition to these bands, the upper area (which we identify as ‘the face’) is bounded by two other inner bands that stop at the first groove, defining the horizontal levels. In this sense, we do not observe a supposed extension downwards and to the right of one of the two borders defined in ‘the face’, as the 2007 interpretation implies. Referring to the same tracing, we observe neither the lower seventh line of this area organised in horizontal stripes nor the transversal grooves of the outermost border on the left side.

As for the painted areas, our spectral classification leads us to consider several clusters in the ochre tones. To put it colloquially, we observe several instances of repainting. In an effort to clarify, we have grouped all the spectral ‘signatures’ of these tones into three classes. Two of them are associated with thick-stroked, dark-toned varieties of thinned applied paint. We suppose they were applied in prehistoric times. One of them, the clearest, is the one on which the descriptions of the classic tracings have been based. The other tone, which is less obvious, enriches the description of some of the most significant elements of the

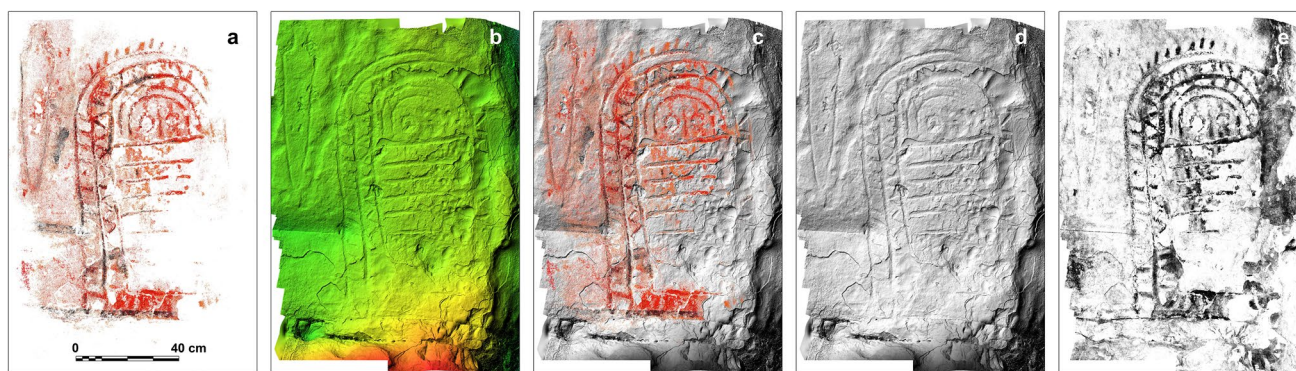


Fig. 22 Different results for the area of the largest anthropomorph and weapon: (a) pigment classification, (b) digital elevation model with hillshade overlayed, (c) pigment classification over hillshade model, (d) hillshade model and (e) pigment absorption band

design. These are features that have remained unpublished until the present day (Fig. 22).

There is a third, more orangey type, which was probably applied with chalk. Although clearly, in some of the strokes, it is difficult to isolate it from other ‘stains’, which we believe to be natural exudations from the rock.

This last type takes us back to an unfortunate recent intervention, specifically from the 1980s. R. de Balbín described it shortly after it took place. A teacher from the surrounding area, with the intention of ‘clarifying’ for his pupils the faded images documented there, traced with chalk several coloured lines in some grooves (Balbín-Behrmann, 1989:29) (Fig. 23). Until now, the extent of this unfortunate intervention was not known. With this work, we have been able to map the areas of deterioration.

The most important discrepancies in the classical tracings are in the decorative conventions of what we identify as ‘the dress’, specifically the number of zigzags and the number of parallel, serial strokes that define its design. Thus, while in the 1914 tracing, the inner horizontal stripes are decorated with parallel serial lines; in the 2007 interpretation, the decoration of this area is based on zigzags. The same is true of one of the arched borders on the head.

Although these areas are difficult to interpret, especially those involving lines not highlighted with an engraving groove, our data lead us to believe these areas were decorated with parallel lines.

The significance of these discrepancies concerns a question of ‘archaeological context’, i.e. formal parallels seen in other examples of anthropomorphic representations from the north of the Iberian Peninsula. Thus, researchers are asking to what extent the conventions of representation of these icons are uniform from one region to another. How the graphic models of representation of ‘power’ were exchanged at the dawn of social portraiture. In this sense, the Peña Tu example is integrated into a larger group of

anthropomorphic images: the well-known Peña Tu/Sejos/Tabuyo group (Bueno Ramirez et al. 2005) (Briard 1993).

As for the elements defining ‘the face’, the most significant discrepancy between earlier tracings and our data must do, once again, with the painted strokes that are not underlined by an engraving groove. All the reproductions identify two engraved and painted circles, which were interpreted as the ‘eyes’ of the figure. Until now, between these two circular shapes, a vertical line painted in red was depicted, which was interpreted as the ‘nose’ (Hernández-Pacheco et al. 1914) (Bueno and Fernández-Miranda 1981) (Barroso Bermejo et al. 2007). We have been able to document two other painted lines parallel to this one, which reach above and below the circles of the eyes mentioned above. They are interrupted by the circles. They are barely perceptible traces and belong to the second of the clusters of prehistoric red paint established in our tonal classification. It is an area with multiple flaking, preventing clear identification of the



Fig. 23 RGB photograph of the detail of the engraved and painted grooves of the larger anthropomorph (Sony αSII—FE 35mm F1.4 ZA). The chalk repainting affecting the protuberances inside the grooves can be seen

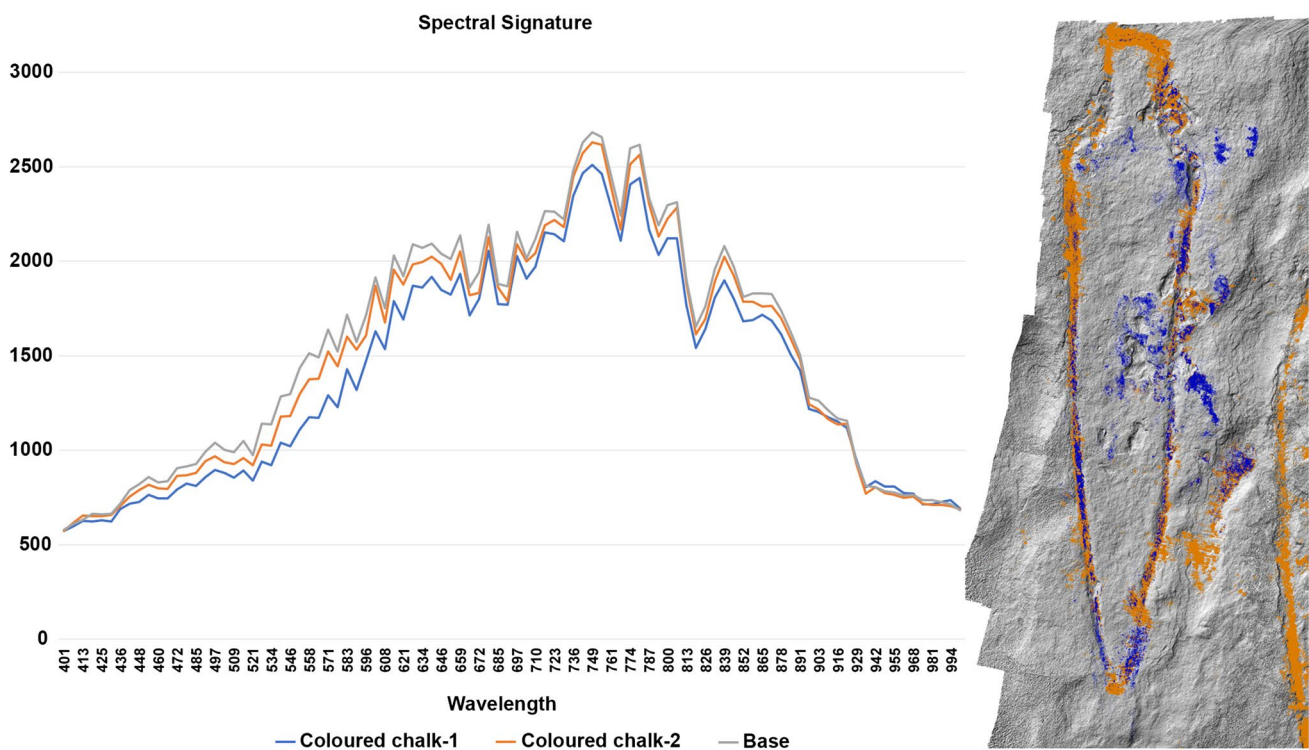


Fig. 24 Spectral signatures of the traces of pigment outlined with coloured chalks and their distribution in the engraving of the weapon in false colour

remaining pigment. We believe it is also possible to identify the extension to the upper arch of the central line, which classical tracings interpret as the ‘nose’. So, in this space of ‘the face’, we can see a total of three parallel vertical lines of similar thickness that reach, at the top, the inner arch of the first border and, at the bottom, the first of the horizontal lines of the ‘dress’.

The weapon

The image of the weapon is one of the key elements in giving chrono-cultural context to the decoration of the panel or part of it. Although, in some publications, its shape has been interpreted as the silhouette of an anthropomorphic tomb (Fernández-Menéndez 1925), most authors agree that its design concerns a weapon. It is a metal weapon with a more or less developed hilt, probably made of perishable organic materials. Sometimes, it is called a dagger (Bueno and Fernández-Miranda 1981, p. 457), and other times, a sword (Almagro Gorbea 1972, p. 67). Sometimes, physical parallels are found in the early stages of the Copper Age metallurgy in the north of the Iberian Peninsula. Other times, it is shifted to the early stages of the Bronze Age. That means we are talking about a period between 2500 and 2000 BC. In technical terms, we would talk about a copper

dagger, the hilt of which is embedded in a metal tang, or a weapon (copper or bronze) with a slightly more complex hilt, in which a system of fastening the hilt with metal rivets cannot be ruled out. This motif has always been observed and described in great detail and has given rise to various discussions about the elements that characterise its design.

The engraving groove has not been the subject of debate in any discussion. At least, successive observers have paid little attention to its description. The type of groove, homogeneous in thickness and U-shaped in section, is similar, although somewhat narrower, to the group of engravings that make up the carved design of the anthropomorphic figure. However, from a purely archaeological perspective, the size ratio (in length and width) between the hilt and the metal blade indicates a type of weapon of relatively large dimensions compared to what is known in the northern third of the Iberian Peninsula (Teira-Mayolini and Ontañón-Peredo 2016). By this, we mean it is more appropriate to speak about a ‘sword’ rather than a ‘dagger’, which would distance us from the early Copper Age weapons mentioned above.

While the technique and features of the line of the groove are not the subjects of debate, the situation is different if we refer to possible traces of paint in the groove itself or inside the surface silhouetted by the groove. Thus, while the groove is unpainted in the 1914 and 1981 publications, the 2007

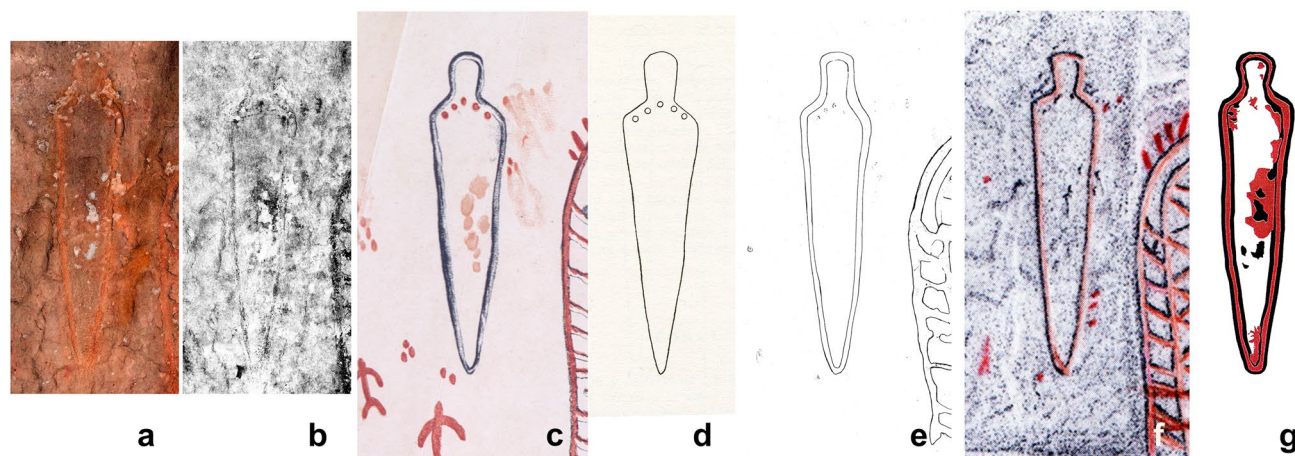


Fig. 25 Different tracings of the weapon of the larger anthropomorph compared with the radiometric data obtained in this work. All cases are shown at the same size, ignoring the inconsistencies of the published scales. **a** Orthoimage with RGB texture. **b** Absorption band for

ochre (600–700 nm). **c** (Hernández-Pacheco et al. 1914). **d** (Almagro Gorbea 1972). **e** (Bueno and Fernández-Miranda 1981). **f** (Barroso Bermejo et al. 2007). **g** (Blas Cortina 2010)

tracing indicates that it was also painted. However, this circumstance is not mentioned in the text of this publication. In this tracing, the stroke painted in red is represented with a colour convention of a fainter tone than that applied to other areas of the anthropomorphic figure. As a third option, in Blas Cortina's interpretation, the entire inner surface of the motif in addition to the groove was painted red (Blas Cortina 2010).

We have been able to observe that this engraving groove was also painted several times using different colouring media. We believe that almost all belong to very recent interventions, probably applied with dry-coloured pencils or with coloured chalk. As in the case of the larger anthropomorph, several orange strokes are superimposed on all the others. Undoubtedly, this is once again the mark of the teacher in his regrettable intervention in the 1980s (Balbín-Behrmann, 1989: 29). The spectral traces of recent interventions are so confused that we cannot be sure whether the groove was painted in prehistoric times using a diluted painting technique. It is possible to distinguish at least two types of colour made with chalk (Fig. 24).

However, as previously described, this orange tone is close to various natural exudations of the rock, so as in the mapping of its tonal family, other stains seem to have nothing to do with the action of the human hand. These stains are associated with small natural concavities, which has led to less exposure of these surfaces to weathering. In the engraving grooves, these recent repaintings can be seen as globular remains adhering mainly to the protuberances of the inner micro-relief without impregnating the bottom of the groove. They have been traced with a dry-coloured pencil.

We also have different descriptions regarding the existence of red dots, which could be interpreted as the rivets

fixing the hilt to the metal blade of the weapon. The 1914 and 1981 publications describe five points in an arc (Hernández-Pacheco et al. 1914) (Bueno and Fernández-Miranda 1981). The 2007 revision, however, states these points never existed (Barroso Bermejo et al. 2007:137). For Blas Cortina, as mentioned above, the supposed dots are only relics of paint on the inner surface of the engraved design, which was covered with pigment. Other authors, such as Almagro Gorbea, accept the interpretation of the five dots drawn in an arc (Almagro Gorbea 1972) (Fig. 25).

We have been able to confirm that there are at least three painted dots in the area corresponding to the grip of the handle, in a position coinciding with that described in the 1914 and 1981 versions, but reduced to three elements. The pigment is similar to that found in the grooves of the anthropomorphic figure; their placement is symmetrical regarding the axis of the engraved silhouette of the sword, and they are in the centre and at the ends of the metal blade. However, this area is dotted with multiple recent, intentional chipping or punctures. We do not rule out the existence of the other two 'dots', although we find it curious that only these three have survived, apparently arranged in axial symmetry (Fig. 26).

In addition to the remains described above, other pigment stains remain on the inside of the silhouette and on the outside, next to the anthropomorphic figure. We could recognise no structured form in them, but their spectral signature is similar to that of other motifs painted to the left of these two larger elements. In this sense, Blas Cortina's interpretation is correct, as he sees the carving and painting of these two figures on the far right of the panel as belonging to a second phase of decoration after most of the working surface had been used (Blas Cortina 2010).

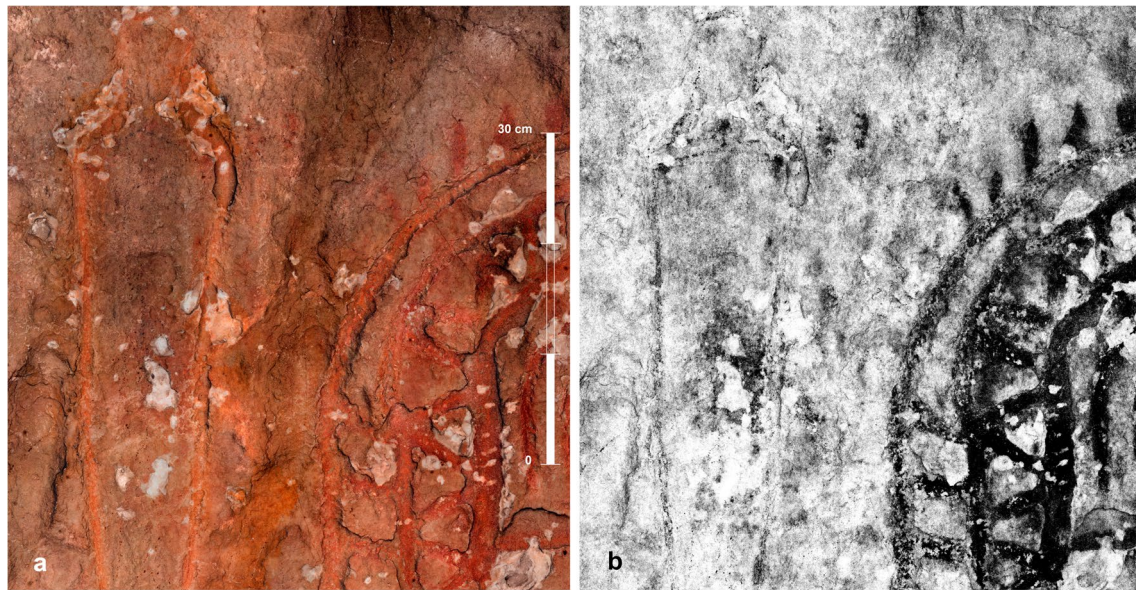


Fig. 26 a, b Detail of the weapon next to the larger anthropomorph. The absorption band for ochre in (b) shows three dots of pigment that we interpret as rivets on the handle

Anthropomorphic figures in the central area of the panel

Between the groups of punctuations on the left of the panel and the large anthropomorphic figure with a sword on the far right, we can see a group of anthropomorphic motifs of standard convention, painted in red: a vertical fusiform trunk, limbs drawn in straight, oblique, downward lines and the head as a mere prolongation of the line of the trunk. It is a ‘scene’. This is how the authors of the 1914 tracing interpret it (a dance) and those of the 2007 version (an aggregation scene). However, the two major differences lie in the identification (or not) of lower limbs in almost all the figures and in the different interpretations of the ‘anthropomorphic figure with staff’ or ‘crook’ in the lower part of the group.

The 1914 tracing reproduces these as complete figures, i.e. with all their limbs, upper and lower, almost like a repeated pattern. The 2007 interpretation is very different, showing no lower limbs in any of the icons. Nor is it easy to agree on the number of anthropomorphs. The ‘Dance’, in 1914, consists of six figures, plus the figure with the crook. These are visible in his graphic proposal, and their number is also detailed in the text of the article (Hernández-Pacheco et al. 1914). As mentioned above, this tracing has no graphic convention regarding natural relief or what the authors consider non-prehistoric. Thus, there are no references to the punctuated motifs of the Christianisation crosses nor to other signs executed with the same technique of more dubious interpretation. Their position is not insignificant regarding the problems of interpretation in this area. The two crosses with orbs (*globus cruciger*) and another simpler one on the

right seriously affect the painted remains of four of the six anthropomorphs. Their location in the tracing could have served as a reference for locating these painted motifs. Thus, in the same way as with the distribution of figures on the far left of the panel, some of these anthropomorphs seem to have been displaced from their actual position. This is noticeable in those on the vertical to the weapon, which have been drawn immediately next to it when they are over 20 cm away. Their location is correct in the 2007 tracing (Fig. 27).

We can interpret the five figures to the right of the crosses with orbs as anthropomorphs because they all have lower limbs. There are undoubtedly more among the amalgam of traces in that area and those between the abovementioned crosses. The clearest figure is to the group’s left, before the figure with the staff. Both the 1914 and 2007 interpretations describe it as an anthropomorphic figure without lower limbs. From our spectral selections, this figure can be interpreted as a repainting of an earlier one that had ‘legs’. The panel was decorated at various times. Not only new figures were added, but also older motifs seem to have been repainted. We can even say there is an overlapping between figures. This can be seen in the far right anthropomorphic figure, whose strokes interrupt a rectangular sign composed of five vertical strokes and another horizontal one that joins them at the top (Fig. 28).

Interpreting the character with the staff or crook has also been conflicting. It is perceived as such in the tracings of 1914 and 1981, unlike in 2007, where the staff becomes an anthropomorphic figure in ‘phi’, who comes with another similar one to his right, with arms appearing as a handle (Barroso Bermejo et al. 2007). Both figures are affected, on

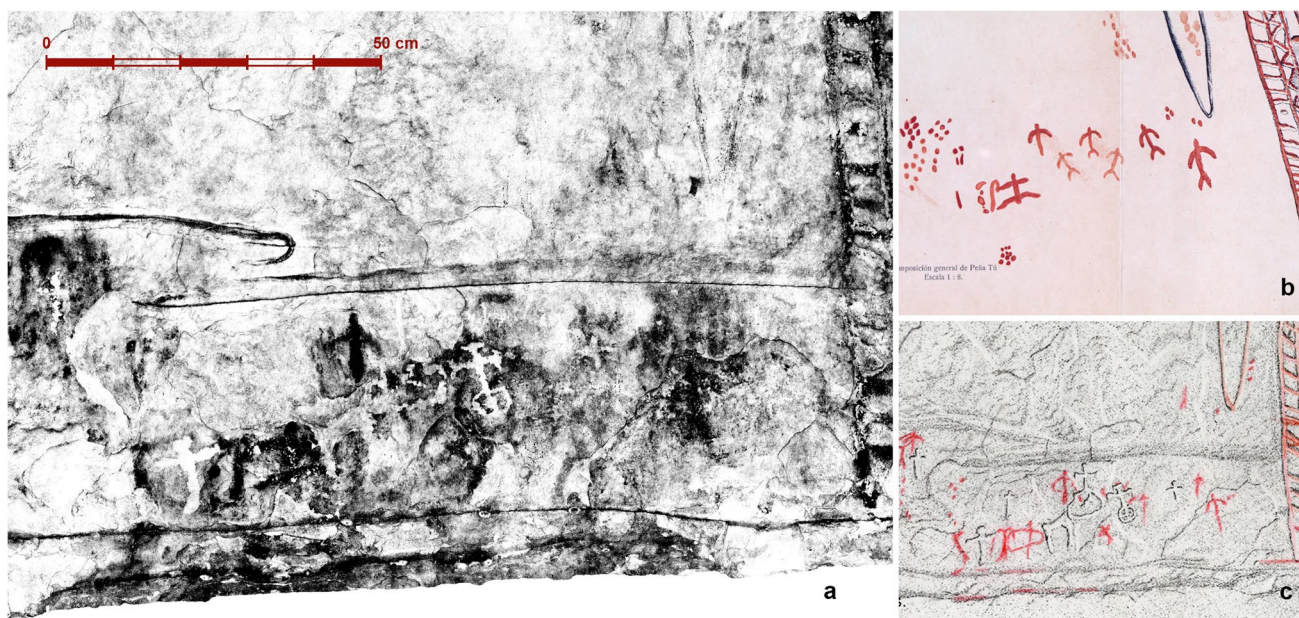
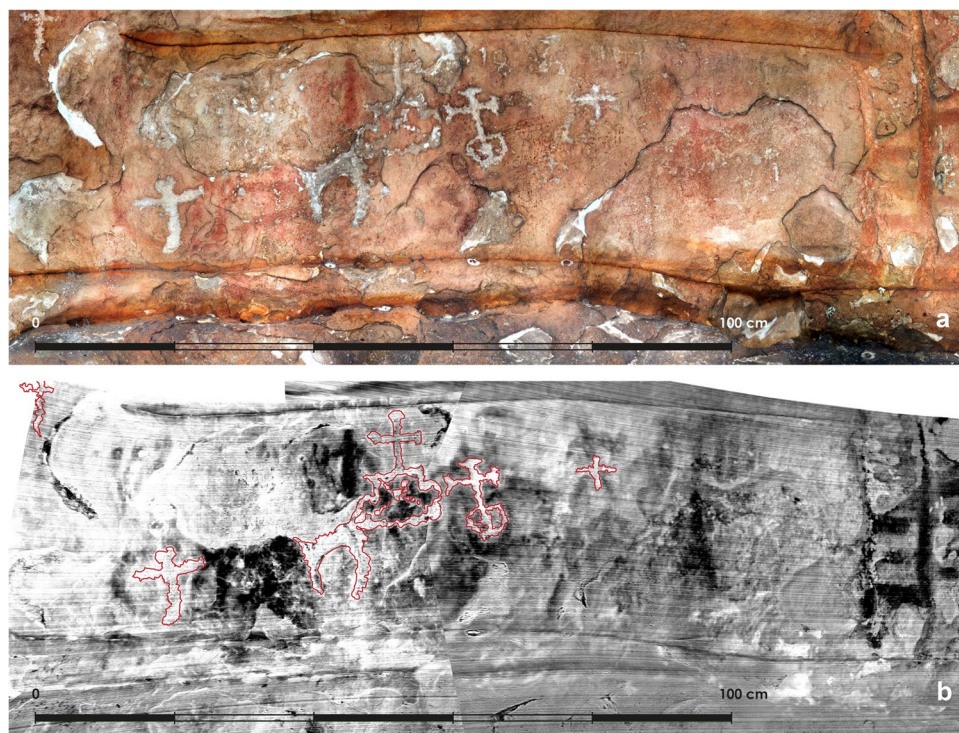


Fig. 27 Anthropomorphs in the central area of the panel. **a** Ochre absorption band (600–700nm). **b** Tracing from 1914. **c** Tracing from 2007

Fig. 28 **a, b** Central area on the upper bench of the panel. In the ochre absorption band, **b** two families of red pigments can be seen, which may indicate two different moments of execution of the decoration



the left and on the right, by two punctured motifs, a cross and a possible zoomorphic figure, which prevent the respective ends of these figures from being analysed.

We believe it is a human figure in a dynamic pose, with its legs open and arms almost horizontal. In this sense, although it reproduces a standard convention, it is a variant for this graphic group. The right arm seems to cling to a vertical linear

element, with a circle or ring at its end. This would identify the crook referred to in the 1914 and 1981 interpretations. However, in reality, the design does not end with this linear line. Next to it, towards the left, up to the alteration of the picket of a cross, we can see other lines clearly linked to the 'staff'. They seem to have three points arranged vertically and other lines with a horizontal tendency. In reality, this reasoning related to

Fig. 29 The ‘figure with staff’, in the central area of the panel. **a** Ochre absorption band. **b** 1914 tracing. **c** 2007 tracing. **d** 2010 tracing



the recognition of staff is based on describing what we think we understand while ignoring the elements for which we find no context in our visual experience (Fig. 29).

Groups of dots and other elements in the centre and far right of the panel

The central and left-hand area of the panel is where we can identify the fewest narrative ideograms. It is an area full of simple geometric elements, mere accumulations of dots, in which researchers have sought to recognise a specific formal order. Two motifs of a somewhat more elaborate design stand out, which we can describe as quadrangular geometric figures and anchor-shaped figures. Perhaps it is the most neglected area in terms of elaborate tracings or textual interpretations. In the 1914 version, we see sets of roughly misplaced strokes. From the quadrangular motif (or quadruped) to the far left of the panel, all the figures depicted are displaced downwards, leaving the horizontal crack decorated with dots above them. In reality, these figures are above this line.

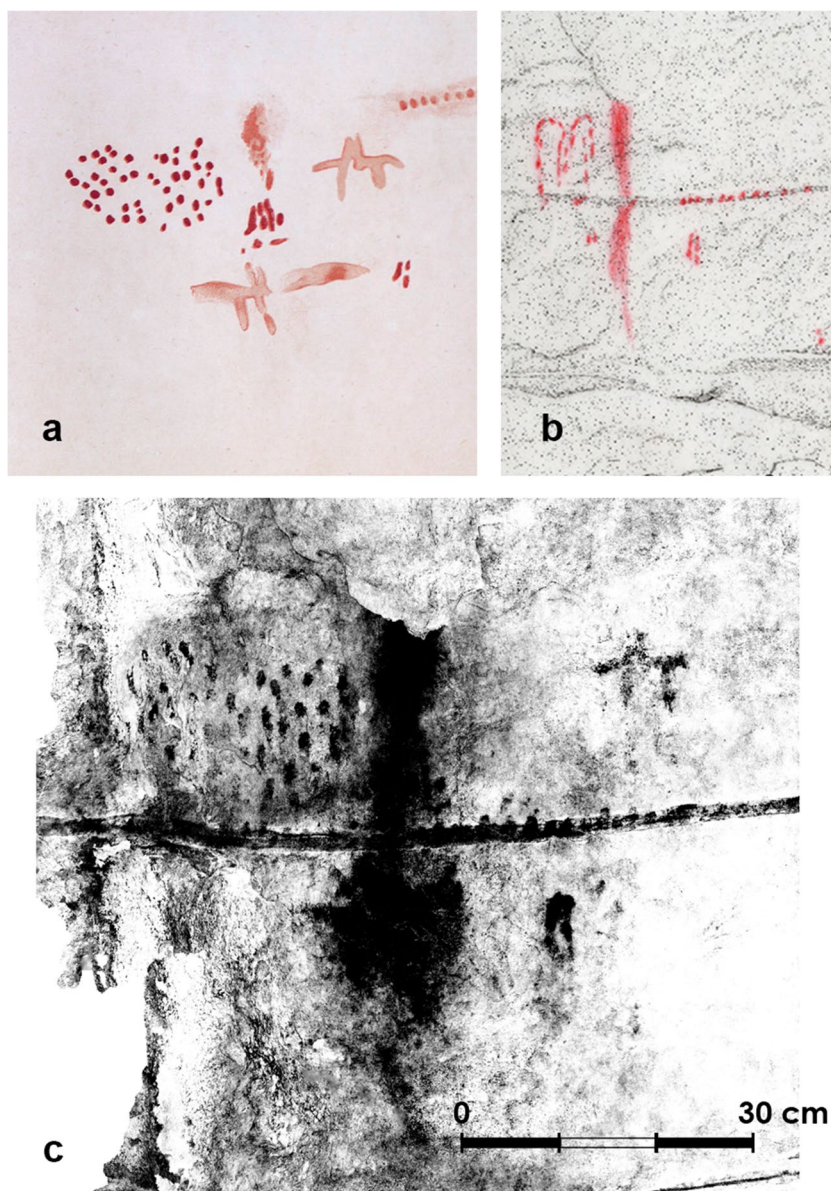
This area at the end is correctly placed in the 2007 interpretation. However, the groupings of dots here become dotted ‘stelliform motifs’, small in size but similar in silhouette to the large anthropomorphic figure at the other end (Barroso Bermejo et al. 2007). Likewise, the quadrangular motif, identified as a ‘schematic animal’ in 1914 and 1981, disappears from his tracing. Our data reveal that this area on the far left has only a nuclear set of dots with no recognisable geometric form. Below this, the end of the crack is decorated, confirmed in this case, with a line of dots. We can also see the ‘animal’ figure, which we prefer to describe as a quadrangular geometric figure (Fig. 30).

The most numerous grouping of dots is found between this group of figures, at the end of the panel, and the area of the figure with the staff. For this area, both the tracings

published in 1914 and 2007 and the descriptions in the texts of their publications, in addition to that of 1981, differ notably. The 1914 interpretation sees internal orders based on curved dotted lines. It even mentions a concave shape (Hernández-Pacheco et al. 1914) which is recognisable in the tracing but which, in reality, acquires its appearance from chipping off the wall. It seems that the writers of the text have described these areas based on Cabré’s tracing (the real draughtsman) and not based on direct observation of the panel. As we have indicated, this tracing shows no modern alterations, whether natural or man-made.

In the 2007 tracing, the density of dots is lower and irregular, with abundant ‘bald spots’ between groups. This is an altered area due to micro-organisms, which have generated a dark biofilm on the rocky surface. This makes it difficult to identify the remains of paint with the naked eye or with commercial RGB sensors. Here, the equipment used in our research has made it possible to document a circular area of about 45 cm in diameter, in which more than a hundred red dots of homogeneous size and dispersion are distributed. They do not seem to be arranged in recognisable shapes. This circular ‘patch’ of dots is delineated by the horizontal cracks in the sandstone strata, which are also decorated with dots. To the right of this area, there is an anchor-shaped figure, damaged on the lower part by the puncturing of a modern cross. This motif was already recognised in 2007 with this label (anchor-shaped), assigning it an anthropomorphic character. This figure comes with another, on the right, which the authors of the 2007 tracing also interpret as anthropomorphic. The lower part of this motif is also changed by more recent flaking. If we accept this anthropomorphic character of the two figures, their graphic convention will differ from the rest of the figures given as such on the panel. They are two designs with a larger side and vertical symmetry, like the other anthropomorphic figures, but with the upper area resolved as an inverted anchor. At least,

Fig. 30 Group of dots and other ideomorphs on the far left of the panel. **a** 1914 tracing. **b** 2007 tracing. **c** Ochre absorption band



this is clear in the figure on the left. The immediate one, on the right, is very deteriorated (Fig. 31).

Traces of paint in the lower back

Finally, the inspection of the lower rock bed of the panel has brought us interesting insights. This has never been reproduced in the various tracings. There is only one brief reference to it in the 1914 publication in which the existence of ten dots below the figure with the crook is noted and is also reflected in his tracing. This publication also refers to ‘vague spots’ (Hernández-Pacheco et al. 1914).

On this lower bed, which is slightly more convex than the upper stratum, almost 1 m high, we have observed various coloured patches. Some are sharper than others. Some have a

specific delineated geometric appearance (Fig. 32). The dots referred to in the 1914 publication, below the figure with the staff, are now seen as two small parallel lines between two horizontal cracks decorated with dots. Below these two cracks, a closed oval shape can be seen, 8cm in length, and perhaps subdivided by other traces inside it, although we may read these details by using some flaking to our advantage (Fig. 33).

In a somewhat riskier reading, we could glimpse a closed rectangular shape, about 70-cm long (vertically), with a horizontal internal division located slightly to the left of the abovementioned shape. Other patches of less well-defined shapes can be seen spreading to the foot of the bed.

Another circumstance which supports the idea that this lower bed had also been decorated is the presence of picket

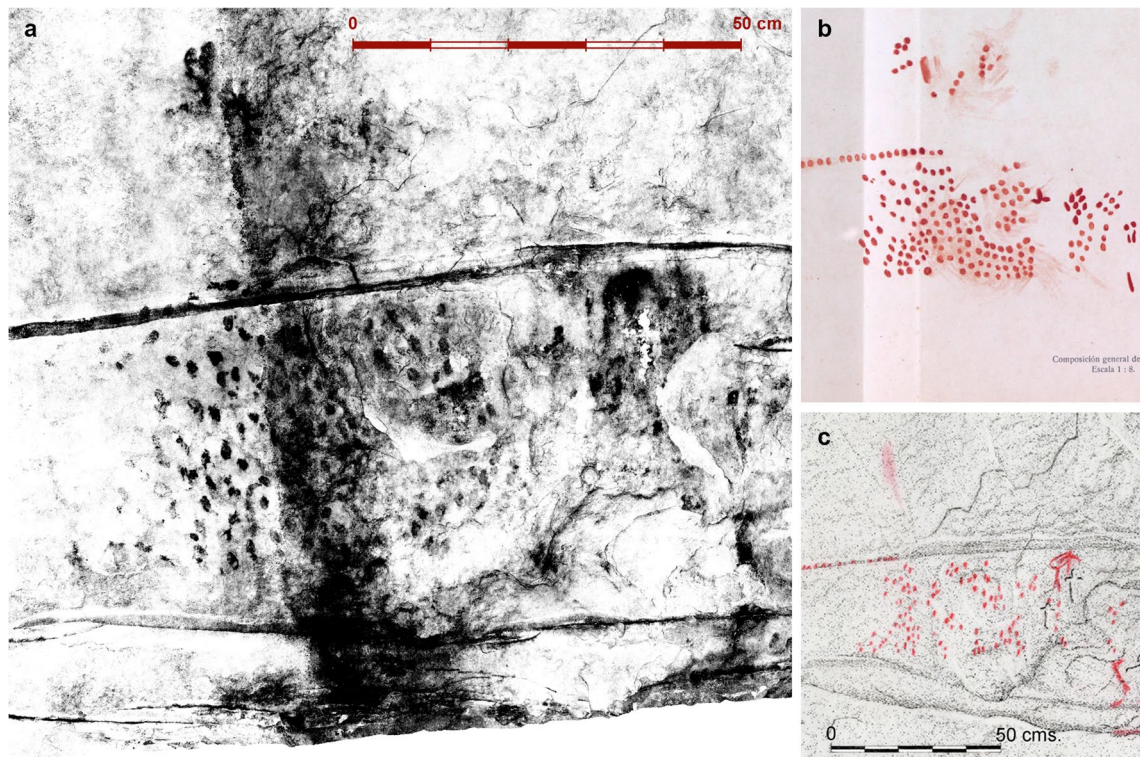


Fig. 31 Dots and ancoriform on the left side of the panel. **a** Ochre absorption band. **b** Tracing from 1914. **c** Tracing from 2007

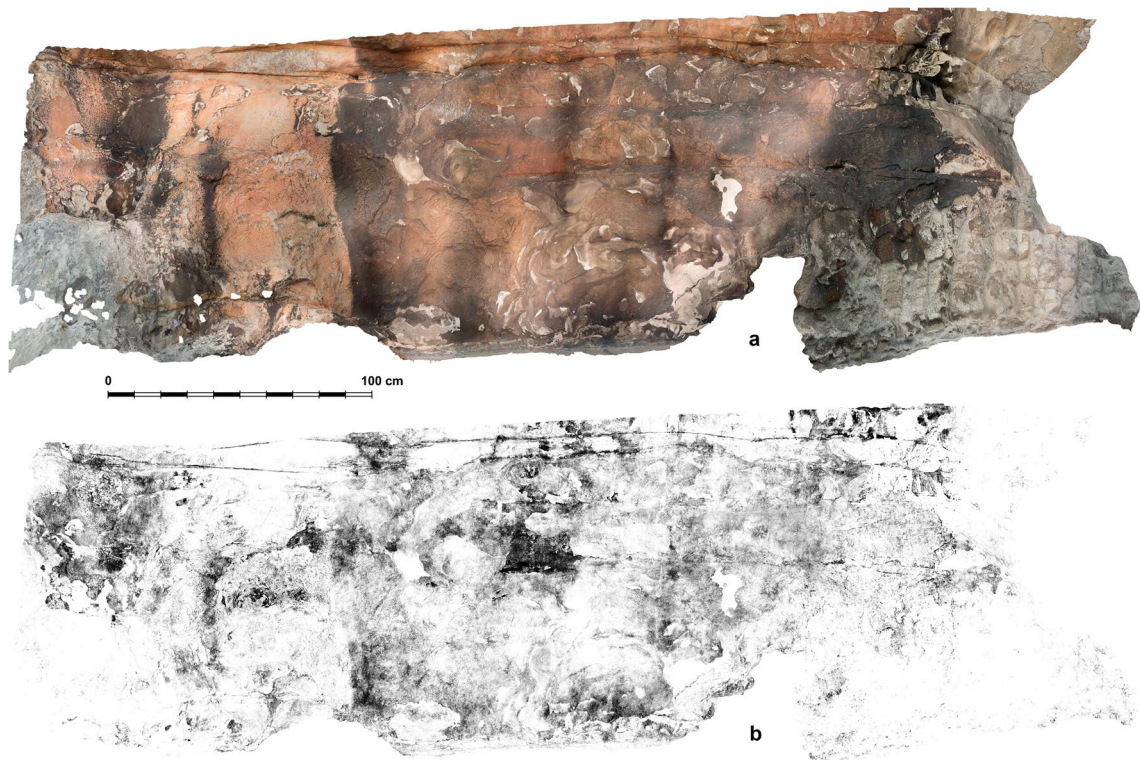


Fig. 32 Lower bench of the panel. **a** Projection to the plane of the RGB texture. **b** Ochre absorption band (600–700 nm)

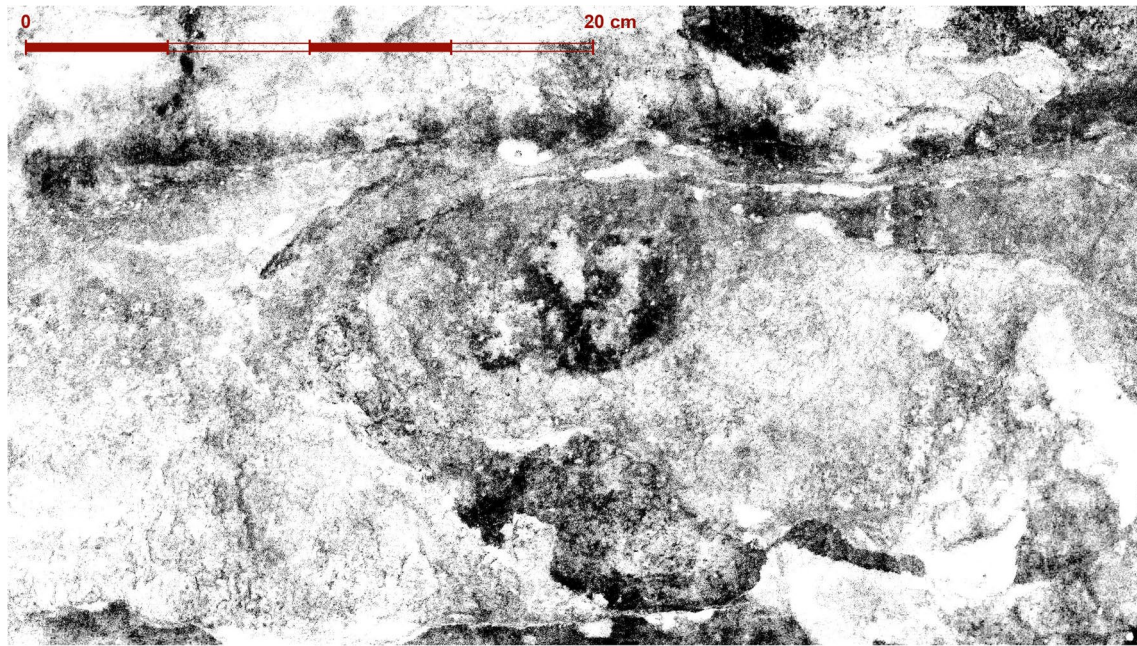


Fig. 33 Detail of the lower bench of the panel. Ochre absorption band

crosses from the Christianisation of the site, as seen among the motifs on the upper panel. Here, there are at least two simple crosses, one of which is of the ‘Jerusalem’ type. This leads us to believe that the figures painted in this area were visible to the naked eye in relatively recent historical times.

Conclusions

The documentation strategy undertaken in Peña Tu shows two main points of interest. One is methodological, and the other is technical.

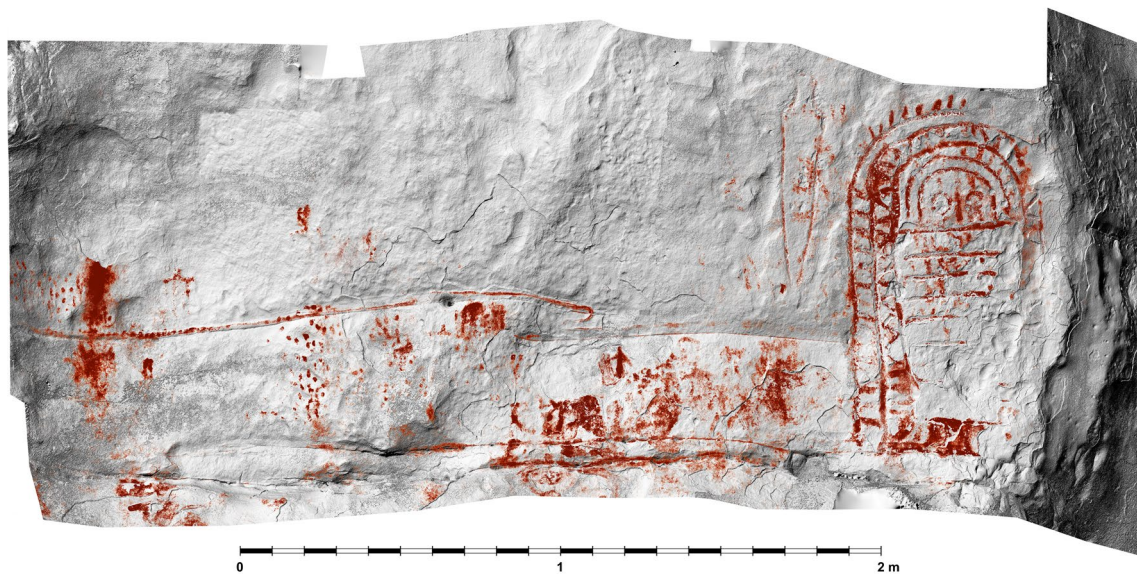


Fig. 34 General view of the upper bench of the Peña Tu panel. The projection plane of this view is detailed in the ‘[Case study: Peña Tu’s rock \(Puertas de Vidiago, Asturias, Spain\)](#)’ section. The false colour

shows the ochre spectral band (600–700 nm), including the recent alterations made with chalk. The rocky support and the engravings are shown as a light/shadow map

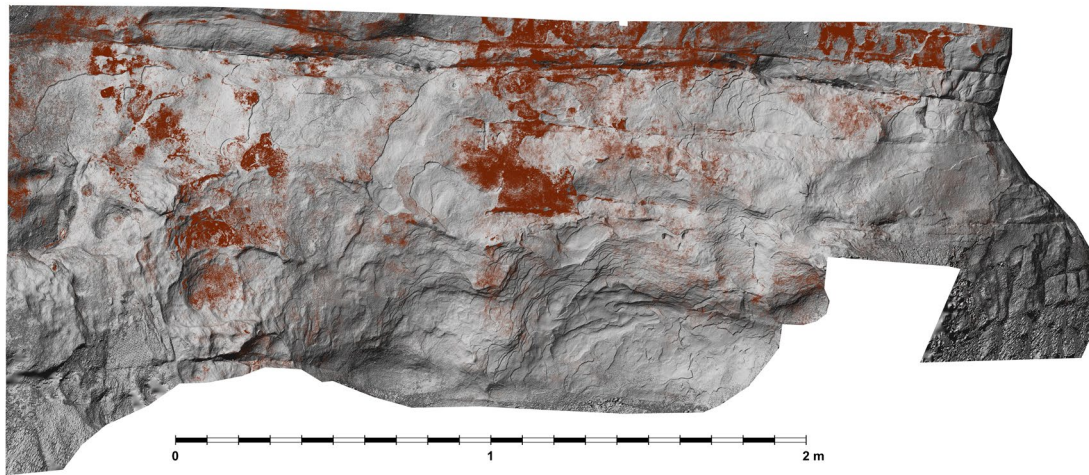


Fig. 35 General view of the lower bench of the Peña Tu panel. The false colour shows the ochre spectral band (600–700 nm). The rocky support and the engravings are shown as a light/shadow map

On the one hand, we have organised a coherent set of quantifiable data, which enables other observers to verify our results. This also lets us reproduce the model in successive examples for comparative purposes. These two circumstances (verification and controlled reproduction) separate this eminently digital model from classical or ‘analogue’ strategies, in which we can distinguish only two single milestones that define its documentation process: the initial physical reality and the final, intrinsically interpretative, tracing.

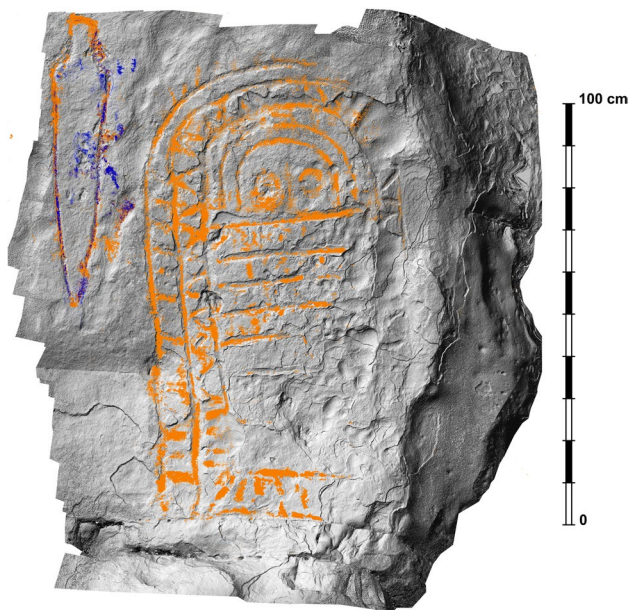


Fig. 36 Image with the dispersion of the dyes attributed to recent repainting with chalk. The rocky support is expressed as a light/shadow map



Fig. 37 Interpretative or ‘third order’ image (Montero Ruiz et al. 1998:157) of the larger anthropomorph and the weapon. Projection of the ochre absorption band shown in false colour, with arbitrary cleaning of the backgrounds. This pigment band has been referenced on the photogrammetric model of the rocky support, expressed as a light/shadow map

In this sense, the documentation of sites with Prehistoric Graphic Expression is on par with other processes in archaeology. In recent years, the generalisation of computer applications has been aimed to a large extent, at measuring those variables of analysis which, in an earlier ‘analogue’ environment, were impossible to systematise. This is especially true in studies where geometry or space are relevant, such as landscape analysis (Figueiredo Daves and Barrocá Faccio 2022; Nakoinz and Knitter 2016) and in micro spatial analysis, in research on human behaviour ‘intrasite’ (Clark and Gingerich 2022; Gopher et al. 2016).

However, research on Prehistoric Graphic Expression has a differentiating circumstance because the form itself (its geometry) has a semantic content. They are designs constructed to be seen and to be read.

This means that the documentation process is confronted by a ‘metalanguage’ belonging to the data (May 2016: 172; Morphy 2005:51), sometimes forcing us to begin our process with subjective choices related to our ability to recognise icons or signs (Beaune 2015). This is more evident with paintings (pictorial stains) than engravings, which we can characterise, with solid criteria, the grooves made by the human hand.

However, we have correctly established two documentation strategies for painting and engraving. The first is eminently radiometric, and the other is geometric. This has also involved an exhaustive parallax control method between the two data sets.

Using a hyperspectral sensor has made it possible to differentiate several families of pigments that can be interpreted as diachronic moments of repainting, at least two of which belong to prehistoric times. With this technique, we have also provided data and obtained complex graphic descriptions of specific icons, which have been conflicted throughout the history of research at the site. This concerns the number and shape of the anthropomorphs, the distribution of the sets of dots and the ideographic interpretation of some of the motifs (Fig. 34). Although it is not the aim of this paper, some of these new descriptions have chronological implications, for example, the combination of painting and engraving found in the depiction of the weapon next to the larger anthropomorph. The dots of red paint on the proximal end of the weapon’s blade can be interpreted as handle attachment rivets, indicating a weapon engineering technique that can be chronologically referenced. Some historical ‘readings’ of this icon refer to five painted dots, but in others, this particular detail does not appear. The aim is to determine whether the weapon belongs to the time horizon of the earliest known copper daggers in the northern third of the Iberian Peninsula or to a later development, in the early Bronze Age, of larger weapons made of alloyed metals. The latter used rivets at the proximal end of the blade to fix the metal blade to the handle. The chronological discussion is very rich and suggestive in terms of the typologies concerned, but poor in terms of the actual weapons found in archaeological sites in these central Cantabrian valleys.

In addition, we have documented new areas with pigment in the lower bench of the quartzite outcrop, whose existence, although mentioned merely as a possibility in the first descriptions (Hernández-Pacheco et al. 1914, p. 7), has not been noted in more recent publications (Fig. 35).

No less important are the parts that refer to the state of the panel’s conservation. With the technique used, we have mapped the extent of the chalk repainting from the 1980s. Although this issue is mentioned in some works (Balbín Behrmann, 1989, p. 29), it has never been possible to obtain a concrete image of such deterioration (Fig. 36).

We have established the relationship between painted strokes and engraving grooves on the larger anthropomorph, which is poorly defined in earlier versions.

To logically conclude the chapter and in our position as prehistorians, we cannot end this study without providing an interpretative or ‘third order’ image (Montero Ruiz et al., 1998, p. 157) of, at least, the major anthropomorphic figure. An image that brings together measured but subjectively selected variables.

Here, it is a matter of tonally matching the two families of ochre paint and their parallax with the rock relief, expressed as a light/shadow map. This convention of the support is the most intuitive for understanding the relief (concave and convex areas). But, as we have explained in the ‘Introduction’ section, as it is a graphic solution within the visual experience, it is difficult to measure (Fig. 37).

The documentation of the Peña Tu site has consolidated, in our experience as archaeologists, a methodological model and a technical praxis. Given the evolution of data capture equipment and analysis software, the latter will obviously have an expiration date. We hope that the work will interest other observers/analysts.

Acknowledgements We would like to thank Dr. Juan José Ibáñez Estévez, a researcher at the Institución Milà y Fontanals of the Consejo Superior de Investigaciones Científicas of Spain (IMF-CSIC), for the loan of the hyperspectral radiometry equipment with which the panels were analysed.

We would also like to thank Eusebio Gutiérrez Roiz, caretaker of the archaeological site of Peña Tu, for his collaboration during the documentation process of the site.

This paper is part of the R&D project PID2020-112832RB-I00, funded by the Spanish Ministry of Science and Innovation (MCIN/AEI/<https://doi.org/10.13039/501100011033>).

Author’s contributions L.T. was responsible for the overall conception of the article. He has written most of the text, especially the methodological and theoretical approach, the data analysis and the conclusions. The contextual photographs, the map made with GIS tools and some of the geometric analysis of the engravings have been done by him. V.B. has been responsible for the technical strategy, both in terms of data collection in the field and their analysis by means of computer applications. The text of the section entitled “Technical scenario and methodology” has been written by him. Most of the images in this section have been generated by him. R.O. has been responsible for the bibliographical context on which the research is based and has been a critical reviewer of the text. E.C. has advised on the technical strategy and has been a critical reviewer of the technical sections. P.A. is the

director of the research strategy in which this study is framed. In fact, he is the Principal Investigator of the research project referred to in the following point (Funding) and in section 10 (Acknowledgements). He has been a critical reviewer of the text, especially with regard to theory, method, discussion and conclusions.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This paper is part of the R&D project PID2020-112832RB-I00, funded by the Spanish Ministry of Science and Innovation (MCIN/ AEI/<https://doi.org/10.13039/501100011033>).

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alfeld M, Baraldi C, Gamberini MC, Walter P (2019) Investigation of the pigment use in the tomb of the reliefs and other tombs in the Etruscan Banditaccia Necropolis. *X-Ray Spectrom* 48:262–273. <https://doi.org/10.1002/xrs.2951>
- Alexopoulou AG, Georgiadou Z, Ilias P, Kaminari AA (2021) The Voyatzis mansion in Aegina, Greece: a historical and architectural approach and physicochemical documentation of the wall painting decoration. *Heritage* 4:3630–3651. <https://doi.org/10.3390/heritage4040200>
- Alfeld M, Mulliez M, Devogelaere J et al (2018) MA-XRF and hyperspectral reflectance imaging for visualizing traces of antique polychromy on the Frieze of the Siphnian Treasury. *Microchem J* 395. <https://doi.org/10.1016/j.microc.2018.05.050>
- Almagro Gorbea M (1972) La espada de Guadalajara y sus paralelos peninsulares. *Trab Prehist* 29(1):55–82
- Aujoulat N (1987) Le relevé des oeuvres pariétales paléolithiques. Enregistrement et traitement des données. (Documents). Editions de la Maison des Sciences de l'Homme
- Balbín-Behrmann R (1989) El arte megalítico y esquemático del Cantábrico. In: González Morales MR (ed) Cien años después de Sautuola. Estudios en homenaje a Marcelino Sanz de Sautuola en el centenario de su muerte, pp 15–96. Diputación Regional de Cantabria. Consejería de Cultura, Educación y Deporte
- Barrera S, Otaola A, Bayarri V (2009) Explotación Turística no Intrusiva de la Cueva de Santimamiñe (Vizcaya) Mediante Realidad Virtual. II Congreso Español de Cuevas Turísticas; Asociación de Cuevas Turísticas Española: Madrid, Spain, pp 359–371
- Barroso Bermejo R, Camino Mayor J, Bueno Ramírez P, Balbín Behrmann R (2007) Los símbolos de los ancestros: el cementerio y las decoraciones de Peña Tú. In Fuentenegros. Un enterramiento del I milenio a.C. en la Sierra de Cuera, Asturias, pp 121–139. Consejería de Cultura, Comunicación Social y Turismo. Principado de Asturias
- Bayarri V, Castillo E (2009) Caracterización geométrica de elementos complejos mediante la integración de diferentes técnicas geomáticas. Resultados obtenidos en diferentes cuevas de la Cornisa Cantábrica. In Proceedings of the VIII Semana Geomática Internacional, Barcelona, Spain, 3–5 March
- Bayarri V, Latova J, Castillo E, Lasheras JA, Heras C de las, Prada A (2015) Nueva ortoimagen verdadera del Techo de Polícromos de la Cueva de Altamira. In Collado H, García JJ (eds) Symbols in the landscape: rock art and its context. (pp. 2309–2320). *Arkeos* no 37. <https://www.researchgate.net/publication/337992659>
- Bayarri V, Castillo E, Domínguez JA (2016) An automatic approach for documentation and recovery of rupestrian paintings using multi-spectral. *Remote Sensing* 7
- Bayarri V, Sebastián MA, Ripoll S (2019) Hyperspectral imaging techniques for the study, conservation and management of rock art. *Appl Sci* 9(23). <https://doi.org/10.3390/app9235011>
- Bayarri V, Castillo E, Ripoll S, Sebastián MA (2021a) Control of laser scanner trilateration networks for accurate georeferencing of caves: application to El Castillo cave (Spain). *Sustainability* 13:13526 <https://doi.org/10.3390/su132413526>
- Bayarri V, Castillo E, Ripoll S, Sebastián MA (2021b) Improved application of hyperspectral analysis to rock Art Panels from El Castillo Cave (Spain). *Appl Sci* 11(3). <https://doi.org/10.3390/app11031292>
- Bayarri V, Prada A, García F, Díaz-González LM, De Las Heras C, Castillo E, Fatás P (2023) Integration of remote-sensing techniques for the preventive conservation of paleolithic cave art in the karst of the Altamira Cave. *Remote Sensing* 15(4). <https://doi.org/10.3390/rs15041087>
- Bayarri V (2020) Algoritmos de análisis de imágenes multiespectrales e hiperespectrales para la documentación e interpretación del arte rupestre. UNED - Escuela de Doctorado
- Beaune SA (2015) Reasoning processes in prehistoric art interpretation. In: Bueno-Ramírez P, Bahn PG (eds) Prehistoric Art as Prehistoric Culture. Studies in Honour of Professor Rodrigo de Balbín-Behrmann, pp 25–29. Archaeopress Publishing Ltd
- Bilius LB, Pentiu SG (2020) Unsupervised clustering for hyperspectral images. *Symmetry* 12(2). <https://doi.org/10.3390/sym12020277>
- Blas Cortina MA de (2010) Poder ancestral y territorio neolítico: en torno a Peña Tú y los túmulos de la costa oriental de Asturias. In: Fernández-Eraso J, Mujika-Alustiza JA (eds) Actas del Congreso Internacional sobre Megalitismo y otras manifestaciones funerarias contemporáneas en su contexto social, económico y cultural (1o. 2007. Beasain, Idiazabal), pp 95–118. Munibe. Suplemento. Sociedad de Ciencias Aranzadi Zientzi Elkarte
- Boardman JW, Kruse FA (1994) Automated spectral analysis: a geological example using AVIRIS data, north Grapevine Mountains, Nevada. Proceedings of The Tenth Thematic Conference on Geologic Remote Sensing
- Bourrillon R, White R, Tartar E, Chiotti L, Mensan R, Clark A, Castel JC, Cretin C, Higham T, Morala A, Ranlett S, Sisk M, Devière T, Comeskey DJ (2018) A new Aurignacian engraving from Abri Blanchard, France: implications for understanding Aurignacian graphic expression in Western and Central Europe. *Quatern Int* 491:46–64. <https://doi.org/10.1016/j.quaint.2016.09.063>
- Briard J (1993) Deesses brisées, deesses armées, deesses et dieux du néolithique à l'Age du Bronze. In: Briard J, Duval A (eds) Les représentations humaines du Néolithique à l'Age du Fer. Actes du 115e congrès national des sociétés savantes, pp 77–84. Comité des Travaux historiques et scientifiques
- Bueno P, Fernández-Miranda M (1981) El Peñatu de Vidiago. In Altamira Symposium, pp 451–467. Ministerio de Cultura.

- Dirección General de Bellas Artes, Archivos y Bibliotecas. Subdirección General de Arqueología
- Bueno Ramírez P, de Balbín Behrmann R, Barroso Bermejo R (2005) Hierarchy and metallurgy: armed statues of the Iberian Peninsula. *Anthropologie* 109(4):577–640. <https://doi.org/10.1016/j.anthro.2005.09.009>
- Cerrillo-Cuenca E, Ortiz-Coder P, Martínez-del-Pozo JÁ (2014) Computer vision methods and rock art: towards a digital detection of pigments. *Archaeol Anthropol Sci* 6(3):227–239. <https://doi.org/10.1007/s12520-013-0147-2>
- Cerrillo-Cuenca E, Bueno-Ramírez P, de Balbín-Behrmann R (2019) “3DMeshTracings”: a protocol for the digital recording of prehistoric art. Its application at Almendres Cromlech (Évora, Portugal). *J Archaeol Sci Rep* 25:171–183. <https://doi.org/10.1016/j.jasrep.2019.03.010>
- Clark AE, Gingerich JAM (eds) (2022) Intrasite spatial analysis of mobile and semisedentary peoples. Analytical approaches to reconstructing occupation history. The University Of Utah Press
- Cortea IM, Ratoiu L, Gher vase L et al (2021) Investigation of ancient wall painting fragments discovered in the Roman baths from Alburnus Maior by complementary non-destructive techniques. *Appl Sci* 11:10049. <https://doi.org/10.3390/app112110049>
- Cucci C, Webb EK, Casini A et al (2019) Short-wave infrared reflectance hyperspectral imaging for painting investigations: a methodological study. *J Am Inst Conserv* 58:16–36. <https://doi.org/10.1080/01971360.2018.1543102>
- Daniel F, Mounier A, Pérez-Arantegui J et al (2017) Comparison between non-invasive methods used on paintings by Goya and his contemporaries: hyperspectral imaging vs. point-by-point spectroscopic analysis. *Anal Bioanal Chem* 409:4047–4056
- Daniel F, Mounier A (2015) Mobile hyperspectral imaging for the non-invasive study of a mural painting in the Belvas Castle (France, 15th C). *STAR: Science & Technology of Archaeological Research* 1:81–88. <https://doi.org/10.1080/20548923.2016.1183942>
- Daveri A, Paziani S, Marmion M et al (2018) New perspectives in the non-invasive, in situ identification of painting materials: the advanced MWIR hyperspectral imaging. *TrAC Trends Anal Chem* 98:143–148. <https://doi.org/10.1016/j.trac.2017.11.004>
- de Viguerie L, Pladevall NO, Lotz H et al (2020) Mapping pigments and binders in 15th century Gothic works of art using a combination of visible and near infrared hyperspectral imaging. *Microchem J* 155:104674. <https://doi.org/10.1016/j.microc.2020.104674>
- Defrasne C, Massé M, Giraud M et al (2023) The contribution of VNIR and SWIR hyperspectral imaging to rock art studies: example of the Otello schematic rock art site (Saint-Rémy-de-Provence, Bouches-du-Rhône, France). *Archaeol Anthropol Sci* 15:116. <https://doi.org/10.1007/s12520-023-01812-6>
- Domingo Sanz I, Villaverde V, López-Montalvo E, Lerma JL, Cabrelles M (2013) Reflexiones sobre las técnicas de documentación digital del arte rupestre: la restitución bidimensional (2D) versus la tridimensional (3D). *Cuadernos de Arte Rupestre* 6:21–32. <https://www.researchgate.net/publication/267737314>
- Domínguez-Cuesta MJ, Valenzuela P, Rodríguez-Rodríguez L, Balasteros D, Jiménez-Sánchez M, Piñuela L, García-Ramos JC (2019) Cliff coast of Asturias. In: Morales JA (ed) *The Spanish coastal systems: dynamic processes, sediments and management*, pp 49–77. Springer. <https://doi.org/10.1007/978-3-319-93169-2>
- Fano Martínez MÁ (1998) El hábitat mesolítico en el Cantábrico occidental. *Transformaciones ambientales y medio físico durante el Holoceno Antiguo*. (J. Hedges, Ed.; Vol. S732). BAR International Series
- Fernández-Menéndez J (1925) La necrópolis dolménica de la Sierra Plana en Vidiago. *Ibérica*, XXIII (581), 360–364
- Figueiredo Daves L, Barrocá Faccio N (2022) Geoenvironmental analysis under the perspective of geographic information system (GIS) and landscape archaeology: Guarani and Kaingang Sites in the Anhumas Stream, Lower Paranapanema Region, SP. In *Springer Proceedings in Earth and Environmental Sciences*, pp 169–184. Springer Nature. https://doi.org/10.1007/978-3-031-05178-4_10
- Fischer C, Kakoulli I (2006) Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications. *Stud Conserv* 51:3–16
- Gopher A, Parush Y, Assaf E, Barkai R (2016) Spatial aspects as seen from a density analysis of lithics at Middle Pleistocene Qesem Cave: preliminary results and observations. *Quatern Int* 398:103–117. <https://doi.org/10.1016/j.quaint.2015.09.078>
- Green AA, Berman M, Switzer P, Craig MD (1988) A transformation for ordering multispectral data in terms of image quality with implications for noise removal. *IEEE Trans Geosci Remote Sens* 26(1):65–74. <https://doi.org/10.1109/36.3001>
- Guertin-Lahoud S, Coursaris CK, Sénécal S, Léger PM (2023) User experience evaluation in shared interactive virtual reality. *Cyberpsychol Behav Soc Netw* 26(4):263–272. <https://doi.org/10.1089/cyber.2022.0261>
- Gutiérrez-Alonso G, Fernández-Suárez J, Gutiérrez-Marco JC, Corfu F, Murphy JB, Suárez M (2007) U-Pb depositional age for the upper Barrios Formation (Armorican Quartzite facies) in the Cantabrian zone of Iberia: implications for stratigraphic correlation and paleogeography. *Special Paper of the Geological Society of America*, 423, 287–296. [https://doi.org/10.1130/2007.2423\(13\)](https://doi.org/10.1130/2007.2423(13))
- Hernández-Pacheco E, Cabré J, Vega del Sella C de la (1914) *Las pinturas prehistóricas de Peña Tú*. In *Trabajos de la Comisión de Investigaciones Paleontológicas y Prehistóricas (Trabajos d)*. Junta para la Ampliación de Estudios e Investigaciones Científicas. Instituto Nacional de Ciencias Físico-Naturales
- Hyvärinen A (1998) Independent component analysis in the presence of Gaussian noise by maximizing joint likelihood. *Neurocomputing* 22(1–3):49–67. [https://doi.org/10.1016/S0925-2312\(98\)00049-6](https://doi.org/10.1016/S0925-2312(98)00049-6)
- Hyvärinen A (1999) Fast and robust fixed-point algorithms for independent component analysis. *IEEE Trans Neural Networks* 10(3):626–634. <https://doi.org/10.1109/72.761722>
- Lemozi A (1929) *La grotte-temple du Pech-Merle. Un nouveau sanctuaire préhistorique*. Editions Auguste Picard
- Li GH, Chen Y, Sun XJ et al (2020) An automatic hyperspectral scanning system for the technical investigations of Chinese scroll paintings. *Microchem J* 155:104699. <https://doi.org/10.1016/j.microc.2020.104699>
- Loeve M (1978) *Probability theory II*. Graduate Texts in Mathematics 46. Springer-Verlag New York
- López-Fernández C, Llana-Fúnez S, Fernández-Viejo G, Domínguez-Cuesta MJ, Díaz-Díaz LM (2020) Comprehensive characterization of elevated coastal platforms in the north Iberian margin: a new template to quantify uplift rates and tectonic patterns. *Geomorphology* 364. <https://doi.org/10.1016/j.geomorph.2020.107242>
- Lorblanchet M (1993) Finalités du Relevé. In *L'Art Pariétal Paléolithique. Techniques et méthodes d'étude* (Comité des, pp 329–337). Ministère de L'Enseignement Supérieur et de la Recherche
- May SK (2016) Learning art, learning culture: art, education, and the formation of new artistic identities in Arnhem Land, Australia. In: Domingo-Sanz I, Fiore D, May SK (eds) *Archaeologies of Art. Time, Place, and Identity*, vol 55, pp 171–194. Routledge
- Montero Ruiz I, Rodríguez Alcalde AL, Vicent JM, Cruz M (1998) Técnicas digitales para la elaboración de calcos de arte rupestre. *Trabajos de Prehistoria* 55:155–169. <http://tp.revistas.csic.es>
- Morales R (2005) Considerations on the art and aesthetics of rock art. In: Heyd T, Clegg J (eds) *Aesthetics and Rock Art*, pp 61–74. Ashgate Publishing Limited
- Morphy H (2005) Aesthetics across time and place: an anthropological perspective on archaeology. In: Heyd T, Clegg J (eds) *Aesthetics and Rock Art*, pp 51–60. Ashgate Publishing Limited

- Le Mouélic S, Chauvet F, Giraud M et al (2013) Investigation of a painting dating the French revolution using visible and near infrared hyperspectral imagery. In: 2013 5th Workshop on hyperspectral image and signal processing: evolution in remote sensing (WHISPERS), pp 1–4
- Mudge M, Malzbender T, Schroer C, Lum M (2006) New reflection transformation imaging methods for rock art and multiple-viewpoint display. In: Ioannides M, Arnold D, Niccolucci F, Mania K (eds) The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage. <https://doi.org/10.2312/VAST/VAST06/195-202>
- Mulholland R, Howell D, Beeby A et al (2017) Identifying eighteenth century pigments at the Bodleian library using in situ Raman spectroscopy, XRF and hyperspectral imaging. *HeritSci* 5:43. <https://doi.org/10.1186/s40494-017-0157-y>
- Nakoinz O, Knitter D (2016) Modelling human behaviour in landscapes basic concepts and modelling elements quantitative archaeology and archaeological modelling. In: Bevan A, Nakoinz O (eds) Springer International Publishing. <http://www.springer.com/series/14342>
- Nielsen F (2020) An elementary introduction to information geometry. *Entropy* 22(10):1–61. <https://doi.org/10.3390/e22101100>
- Ontañón R, Bayarri V, Herrera J, Rodríguez R (2014) The conservation of prehistoric caves in Cantabria, Spain. In: Saiz-Jiménez C (ed) The Conservation of Subterranean Cultural Heritage, pp 185–192. CRC Press/Balkema. Taylor & Francis Group. <https://www.researchgate.net/publication/271211021>
- Pires H, Gonçalves-Seco L, Fonte J, Correia Santos MJ (2014) Morphological residual model: a tool for enhancing epigraphic readings of highly eroded surfaces. In: Orlandi S, Santucci R, Casarosa V, Liuzzo PM (eds) Information Technologies for Epigraphy and Cultural Heritage. Proceedings of the First EAGLE International Conference, pp 133–144. Sapienza Università Editrice. <https://www.researchgate.net/publication/306202065>
- Raphael M (1986) Trois essais sur la signification de l'Art pariétal paléolithique. Le Couteau dans la plaie/Kronos. Paris
- Richards JA (1986) Remote sensing digital image analysis: an introduction. Springer-Verlag Berlin Heidelberg. <https://doi.org/10.1007/978-3-662-02462-1>
- Rivera Jiménez T, García Sanjuán L, Díaz-Guardamino M, Donaire Romero T, Morales González JA, Lozano Rodríguez JA, Rogerio Candelera MÁ, Bermejo Meléndez J, Aguilera Collado E (2021) The Cañaveral de León stela (Huelva, Spain). A monumental sculpture in a landscape of settlements and pathways. *J Archaeol Sci Rep* 40. <https://doi.org/10.1016/j.jasrep.2021.103251>
- Rogerio-Candelera MA, Linares JA (2015) El análisis digital de imágenes como herramienta arqueológica. Estudio de los restos de pintura de los ortostatos del dolmen 3 de El Pozuelo. Estudio y Conservación Del Patrimonio Cultural. *Actas.*, 82–85
- Sabins FF (1986) Remote sensing principles and interpretation (2nd ed). W. H. Freeman and Co
- Schmitt B, Souidi Z, Duquesnoy F et al (2023) From RGB camera to hyperspectral imaging: a breakthrough in Neolithic rock painting analysis. *Herit Sci* 11:91. <https://doi.org/10.1186/s40494-023-00940-5>
- Soska KC, Adolph KE, Johnson SP (2010) Systems in development: motor skill acquisition facilitates three-dimensional object completion. *Dev Psychol* 46(1):129–138. <https://doi.org/10.1037/a0014618>
- Storrs KR, Fleming RW (2021) Learning about the world by learning about images. *Curr Dir Psychol Sci* 30(2):120–128. <https://doi.org/10.1177/0963721421990334>
- Teira Mayolini LC, Ontañón Peredo R (2016) Estatua-estela de Salcedo (Valderredible) y los inicios del retrato social en la Prehistoria. In: Serna Gancedo ML, Martínez Velasco A, Fernández Acebo V (eds) Después de Altamira. Arte y grafismo rupestre post-paleolítico en Cantabria, pp 45–51. Acanto. Asoc. Cántabra para la Defensa del Patrimonio Subterráneo
- Teira-Mayolini LC, Ontañón-Peredo R (2016) Conjunto de hitos y estelas del Collado de Sejos. In: Serna Gancedo ML, Martínez Velasco A, Fernández Acebo V (eds) Después de Altamira: Arte y grafismo post-paleolítico en Cantabria, pp 271–276. Acanto
- Ucko PJ (1989) La subjetividad y el estudio del arte parietal paleolítico. In: González Morales MR (ed) Cien años después de Sautuola: estudios en homenaje a Marcelino Sanz de Sautuola en el Centenario de su muerte, pp 283–358. Gobierno de Cantabria, Consejería de Cultura, Educación y Deporte

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

Authors and Affiliations

Luis Teira¹  · Vicente Bayarri^{2,3}  · Roberto Ontañón^{1,4}  · Elena Castillo⁵  · Pablo Arias¹ 

✉ Luis Teira
teiral@unican.es

Vicente Bayarri
vicente.bayarri@gim-geomatics.com

Roberto Ontañón
ontanon_r@cantabria.es

Elena Castillo
elena.castillo@unican.es

Pablo Arias
ariasp@unican.es

¹ Instituto Internacional de Investigaciones Prehistóricas de Cantabria, Universidad de Cantabria/Gobierno de Cantabria/Santander, Santander, Spain

² Gim Geomatics, S.L., Torrelavega, Spain

³ Polytechnic School, Universidad Europea del Atlántico, Santander, Spain

⁴ Museo de Prehistoria y Arqueología de Cantabria, Santander, Spain

⁵ Departamento de Ingeniería Geográfica y Técnicas de Expresión Gráfica, Universidad de Cantabria, Santander, Spain