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Applications of digital photography in the study of Paleolithic cave art

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ABSTRACT

Developments in digital methods of rock-art study in Western Europe have considerably diversified and enriched this field of research in the last 25 years. This is especially the case for microanalyses of artistic materials (datings, pigment characterization, etc.), and also for the study of the images themselves, their topography, their positioning and their contexts. 3D analyses, software with colorimetric filters, and macro-microscopic imaging represent examples of promising new tools for the study of rock art.
The object of this article is to show some of these tools' applications in the context of decorated caves through specific cases taken from the study of several caves in France: Blanchard (Indre), Les Gorges (Jura), Rouffignac and especially Les Bernoux (Dordogne). The contributions of several applied techniques highlight the importance of their use in combination. This includes first of all photography, and multiple scientific applications of digital photographs such as photogrammetry, macrophotography and decorrelation stretch (colorimetric treatment).
This article provides a synthesis of different results, in order to show the potential of these methods, especially for their use in combination. We emphasize in particular the contribution of decorrelation stretch, used to enhance the reading of color and pigments.

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1. Introduction and objectives

The development of digital methods in the study of prehistoric art, especially in rock art, has considerably diversified and enriched this field of research in the last 25 years. This is especially the case for microanalyses of the artistic materials (in particular for dating and pigment-characterization), but also for the study of the images themselves, their topography, positioning, and contexts.

Large and immovable surfaces like cave walls are frequently digitally modeled, largely to address conservation or mediation concerns. The applications for research are maybe less common and have shown increasingly significant results, with clear contributions to scientific knowledge.

Several of these processes are based on photography: it provides a high degree of flexibility and precision in recording and different substantial possibilities for data extraction assisted by efficient software programs.

We aim to demonstrate how these tools have been applied in decorated caves and their utility for research issues: the discovery of new figures, discernment of "technical facies" and drawing techniques, plotting of the organization of representations in the cave, and restitution of their contexts. We present here a synthesis of some selected recent results to show how these processes can be adapted to different kinds of cave contexts in Paleolithic rock art, and why their combination is profitable to scientific data-collection and research.

2. Approaches and digitalization

Digital techniques of analysis have been applied to prehistoric art to meet three primary areas of interest: the context of the art, the identification and analysis of representations, and finally, the technical gesture and traceological approaches.

Primarily, 3D modeling allows for the recording of large areas, especially significant volumes of decorated surfaces (topography, galleries, walls) with high precision. This is also particularly necessary for recording and rendering at a smaller scale, such as fine works like engravings. The scale and resolution of the observation as well as the tools employed have to be adapted to scientific objectives. Modeling could be used in particular for reconstitution of cave context, or large decorated panels. In general, the scope of the analysis must be increasingly constrained by the level of desired details (Delannoy et al., 2010; Burens et al., 2011; Pastoors and Weniger, 2011; Azema et al., 2013).

Secondly, digital approaches have been particularly efficient in identification and analysis of representations (Fritz et al., 2010; Pinçon

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et al., 2010), and can be used for survey as well (Feruglio et al., 2015). In the area of colorimetry, decorrelation stretch has been applied to further the identification and interpretation of paintings and pigments. These methods reveal recovered, obscured, or altered pigment representations, even if they are nearly invisible to the naked eye. Different systems of algorithms have been applied, first of all in the context of open-air rock art (among examples Le Quellec et al., 2013; McDonald et al., 2014). This method was also applied to the study of cave art (Ruiz-Redondo et al., 2015; Man-Estier et al., 2015). It allows for the enhancement of faded paintings and aids in their systematic survey.

Lastly, macro- and microscopic analyses are applied to the identification and characterization of technical stigmas and traces. These approaches have been applied on Paleolithic portable art in laboratory settings (D'Errico, 1994; Fritz, 1999; Mélard, 2010, Rivero, 2011). Other new approaches provide original and non-invasive means of analysis of engravings (Bello et al., 2013). A large part of the equipment employed in laboratory settings (notably electron microscopes) cannot be used in cave contexts. Alternative approaches are currently being investigated (Plisson, 2014), especially the use of very high resolution photography.

The methods developed from digital photography and software allow investigations in these three techniques: photogrammetry, macrophotography, and decorrelation stretch. They offer a large variety of scales, from overviews to high-precision details, increased perception of colors, and allow more flexibility in response to the many constraints of cave environments. They also present the advantage of being cheaper than alternative approaches.

Additionally, ultraviolet or infrared photography have been used for the analysis of paintings, primarily to assist in the recognition and reading of red and black pigments (for example Fredlund and Sundstrom, 2007). These digital tools and the development of specialized software applications have presented improved possibilities for the application of photography in archaeological research, especially for the study of prehistoric representations.

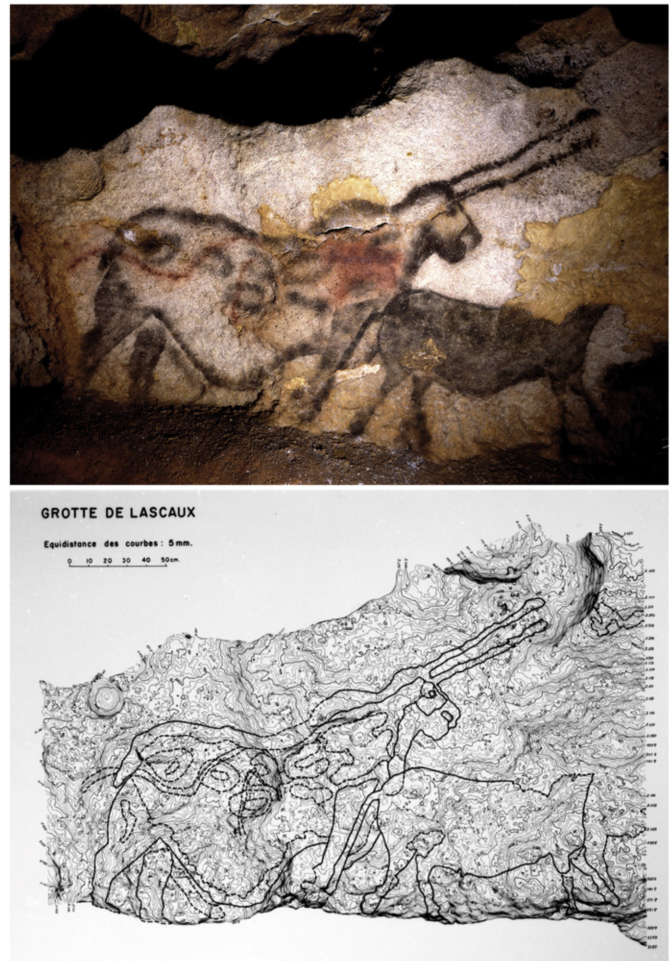

Fig. 1. Photo and digitalization by photogrammetry of Unicorn, Lascaux, IGN.

3. Methodologies implemented

3.1. Photogrammetry

Among available digital applications, photogrammetry has taken an important place in the study of rock art. It was experimented with during the 20th century, with the process of stereoscopic photography, at the cave of les Trois Frères in 1912 (Ariège), and by IGN in Lascaux cave (Dordogne) (Fig. 1), or as a more recent example, the *Frise Noire* in Pech Merle (Lot) (Lorblanchet, 1979). The underlying principles of photogrammetry remain the same, but new possibilities are offered with digital technologies, notably in the context of cave-art studies, where new applications of this methodology are being applied.

Here, we address close-range photogrammetry (or CRP), where the camera is close to the subject. Hand-held or with a tripod, this process responds to the requirements of computer analysis, instead of stereoscopic pairs, which are the origin of the methodology. The revolution of digital images has been expanded with increased computer capacity and access to free software (open source) since the 2000s. Photogrammetry is achieved by the combination of images taken from several angles in order to obtain a precise three-dimensional representation of any object that can be photographed (Egels, 2011). There are two phases: the initial digital photography and the software-aided treatment of the photographic data (the pixel).

In order to get exhaustive details of a decorated panel and to establish accurate pixel correlation between images, we followed a protocol based on successive photographs with large areas of overlap (more than 50%) between fields of view. This recording process also requires imaging from several angles (3 to 5 or more) to capture the depth and relief of form of the subject. Consistent camera settings have to be maintained, as well as stable lighting conditions without any zones of shadow, in order to achieve efficient correlation, enough detail, and satisfying textural information.

The resolution of the 3D model is determined by the frame size (which represents the number of pixels) of the camera sensor. The use of a full frame camera (24 × 36 mm) and the selection of an appropriate lens ensure accuracy. Photogrammetry also requires a consistent focal distance from the subject and a high focal length to maximize the depth of field. A very high resolution requires greater proximity with the decorated panel. A tripod is required for stability and maintenance of a consistent position. In order to obtain efficient 3D models of decorated walls, it is necessary to cover every visible part of the subject, hence the variety of angles, to promote aerotriangulation, which provides the background structure of the model, calculated by algorithms.

The second stage of the photogrammetry technique concerns the modeling process performed automatically by computing and calculating algorithms, pre-established by various software programs, such as Photoscan®, Arc3D® or 123D Catch®.

Regardless of the software employed, there are several phases to this operation. The first one, which is aerotriangulation, reconstitutes the image-capture configuration (orientation and position of the camera) based on the recognition in each image of corresponding landmarks. The second phase, dense correlation, builds a geometrically accurate volumetric model based on similar pixels in corresponding images. These two phases produce a point-cloud that is then meshed by triangulation, and finally textured with the same pictures which were used for each phase of construction of the 3D model.

This process has been applied in many caves, like Rouffignac (Dordogne) and Blanchard (Indre), through collaboration between prehistorians and specialists in photogrammetry (Robert et al., 2014a). In both caves we used software Apero® and Mic-Mac® (Pierrot-Deseilligny and Cléry, 2011). The example of Rouffignac underlines specific adaptations of the process, depending on technical attributes and dimensions of representations.

In Rouffignac Cave, within the framework of the program ANR-MADAPCA (Paillet, 2014), we tested photogrammetry at several scales of precision (from 1 mm to 50 μm) on two decorated panels, which contain different kinds of marks, and drawings of variable width and depth. The method applied was dense-correlation image-matching.

On the Tectiform 29 panel, these techniques were applied at scales ranging scales from 4 m (the whole panel from) to 15 cm (a specific window inside tectiform base). For aerotriangulation, we used a Nikon D3 camera with 24 mm lens (pixel range at 1 m: 0.35 mm). For dense correlation on the base of the tectiform sign, we used the same camera but with a 105 mm lens (pixel range at 1 m: 0,08 mm).

On the Patriarch panel, several techniques of drawing were employed by Paleolithic artists. Among them are a rhinoceros representation whose the engraved profile presents a distinctly rounded form, one mammoth drawn with a fingertip, and the mammoth known as the Patriarch, superimposed on the two figures. Its furry coat has been vigorously etched on its surface with a sharply-pointed burin. These anthropogenic actions to the cave wall are mixed in with claw-marks of cave bears.

In order to record this area (Fig. 2), the whole panel was recorded for aerotriangulation with photography on manual settings (Pentax K5 camera, 28 mm) with oblique lighting (2 cobra flashes), followed by a higher-resolution series of pictures for dense-correlation: 72 photos with 120 mm lens (pixel range at 1 m: 0,04 mm). This method allowed for faithful imaging of all of the different traces of animal and human origin on the panel, facilitating a complete restoration by 3D-rendering of this complex surface. Tests of lighting were particularly important because the orientation of the lighting source must be precisely established for the capturing of the volume of the engravings and cave surface. This example illustrates the potential of adaptation capacity of photogrammetry technique to the context of decorated caves, especially for fine engravings and uneven surfaces or access difficulty.

Photogrammetry in cave contexts is also useful at larger scales, in order to capture the volume and contour of cave walls, which also contribute to the reconstitution of the representations' context.

In the cave of les Gorges (Jura) we were able to achieve a complete three-dimensional rendering of the decorated ceiling. This cave was discovered in 2009 and presents many series of lines, as well as several animals: horses, felines or megaceros (David et al., 2014). There are furthermore many engraved blocks, with tracings and animal representations (horses, rhino, deer), and a little statuette that represents a bear head.

The cave is small in dimension (13 m of depth, 7 m of greatest wide), and all representations are engraved on the ceiling, which covers 32 m^2. With a Nikon D90 camera, we used 18 mm lens to get the largest surface-covering, with the couple f: 11, 1/200e to reconstitute all volumes of the ceiling. 106 photographs have been taken, under three different angles (Fig. 3). Lighting was placed in front of the ceiling. We obtained the point cloud with Photoscan® and the resulting mesh was more than 12 million faces. Accuracy level was lower than accuracy level for engravings, at millimeter. The most important thing was the respect of volumes.

In order to analyze and reconstitute the organization of different kinds of tracings and animal prints, we produced an orthophotographic picture from the model, faithfully reconstructed in its dimensions. Moreover, with photographic imaging, we had the possibility to digitalize unreachable volumes of the complex ceiling surface. From this orthophotography, we were able to re-situate all of the graphic entities as well as animal scratches in the cavity, and reconstruct the context of the representations (Fig. 4).

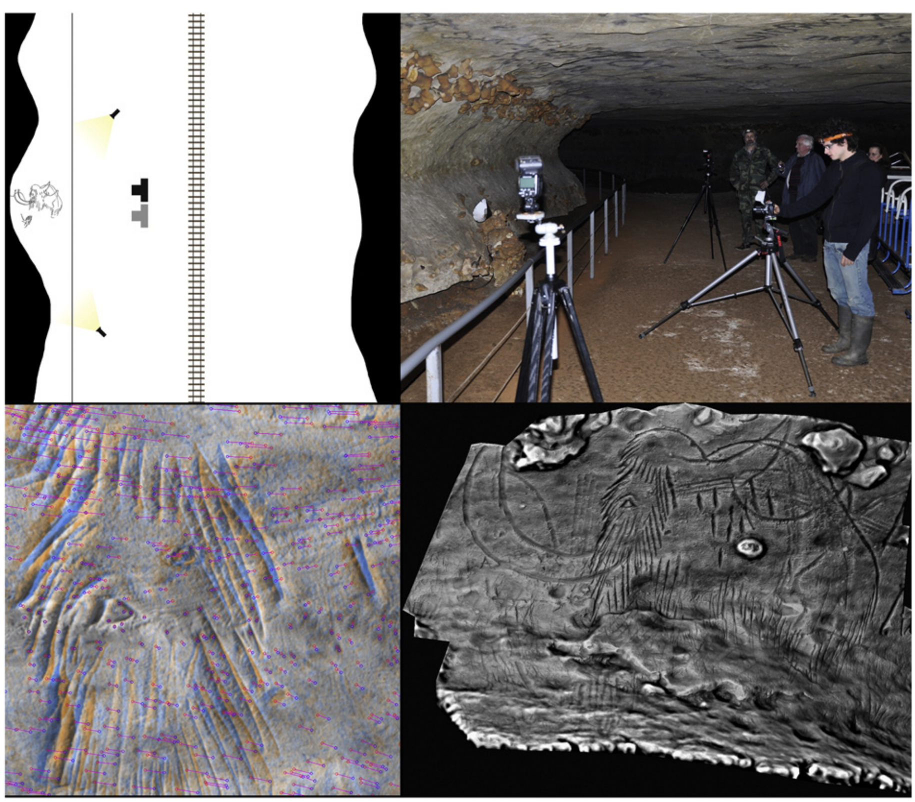

Fig. 2. Photogrammetry of the panel of the Patriarch, Rouffignac Cave, showing: position of cameras and lightning, homologous pixels on the head of the mammoth, model of the mammoth.
(Software: MicMac, M. Pierrot-Deseilligny, IGN)

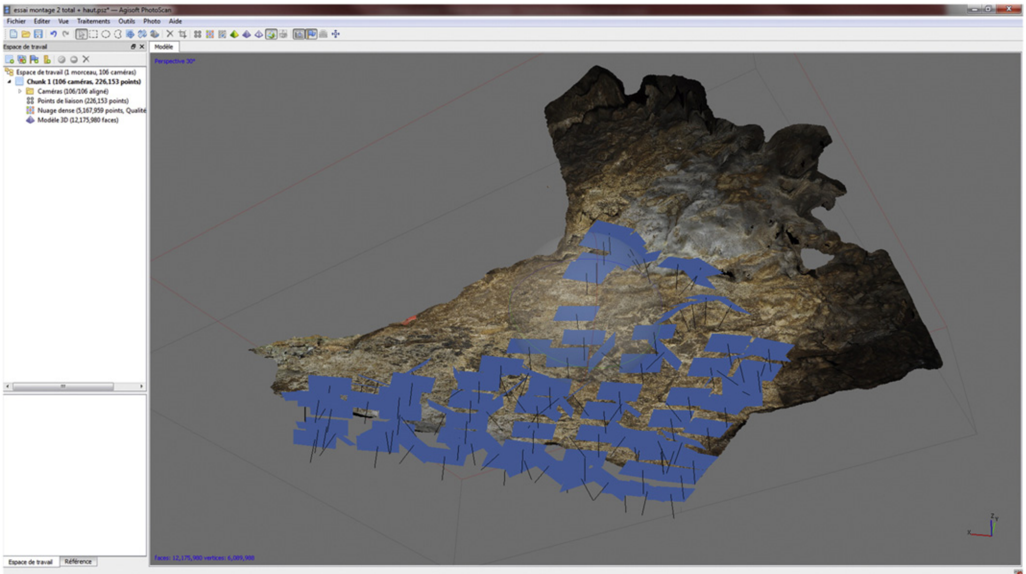

Fig. 3. Position of cameras in digitalization of the ceiling of Les Gorges Cave, with Photoscan (Agisoft). (Doc. E. Robert)

3.2. Decorrelation stretch

In cave contexts, as in open-air rock art, determining the colors of pigments and their evolution in conservation remains of the main challenges. This includes seeing and decrypting traces of color to register those that are partially or mostly recovered, as well as obscured or altered paintings that are sometimes nearly invisible to the naked eye, sometimes rendered invisible by superimposition (Gunn et al., 2010).

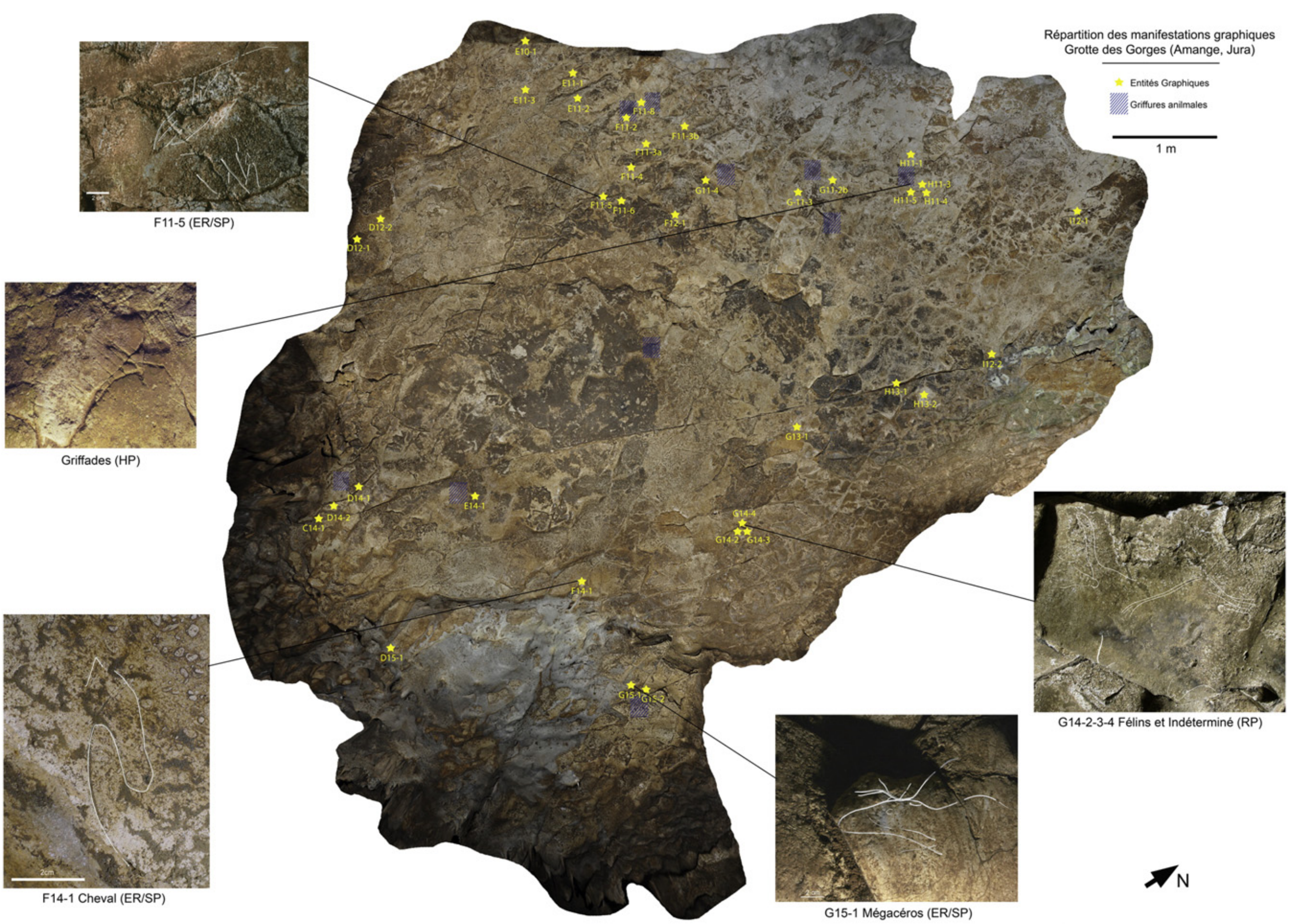

Fig. 4. Cartography of the ceiling of Les Gorges. (Doc. S. Petrognani, E. Robert, S. David, R. Pigeaud)

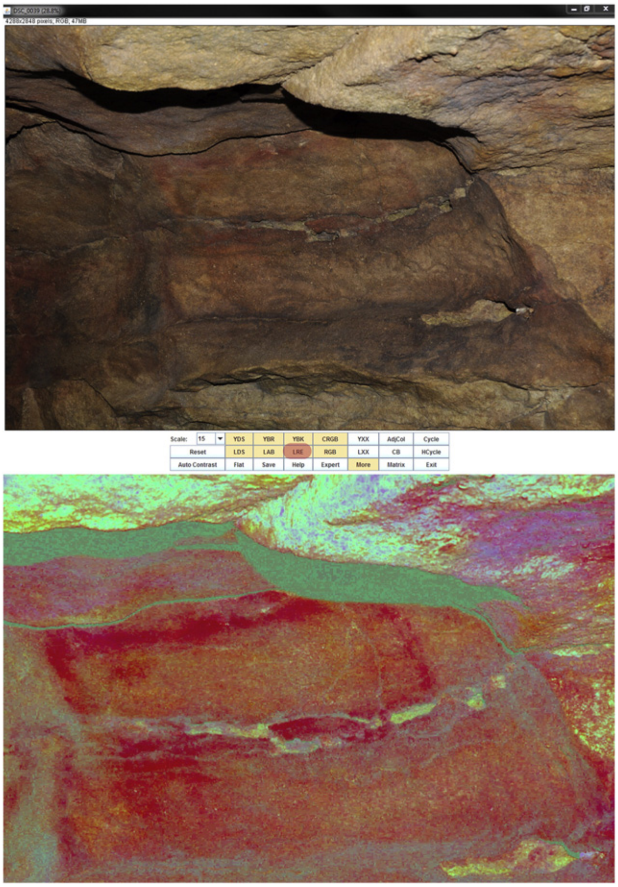

Fig. 5. Presentation of D-Stretch plug-in (developed by Jon Harman) in Image J software (National Institute of Health), example of red sign, Blanchard cave, photo and D-Stretch LRE filter.
(Docs. E. Robert)

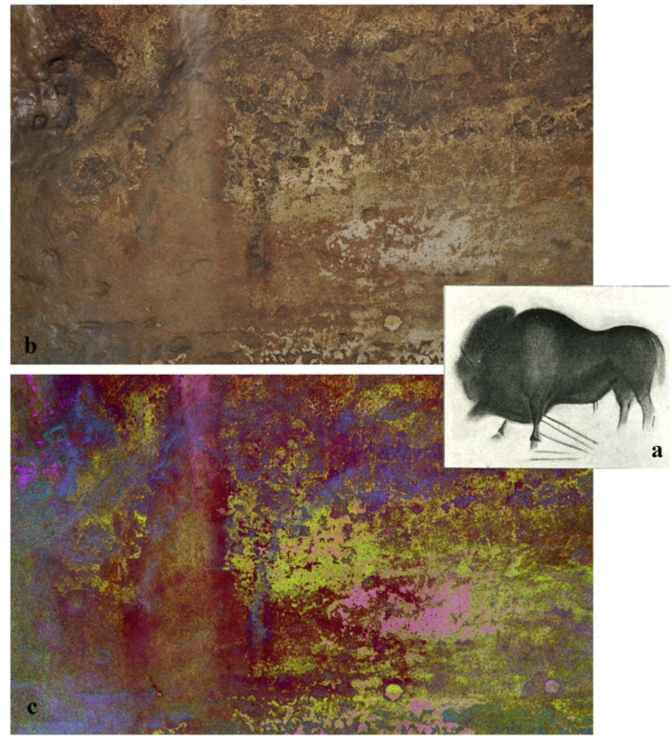

Fig. 7. Application of D-Stretch software on a tectiform sign in Font-de-Gaume: photography and YRE D-stretch filter (docs. E. Robert), survey H. Breuil (1910) of bison and tectiform.

Different techniques can be applied to reveal these traces, including infrared or ultraviolet fluorescent light. These methods are often used for open-air rock art contexts, but they present specific obstacles to use in cave environments: they require large equipment such as emission sources, filters, and specific cameras made to register infrared

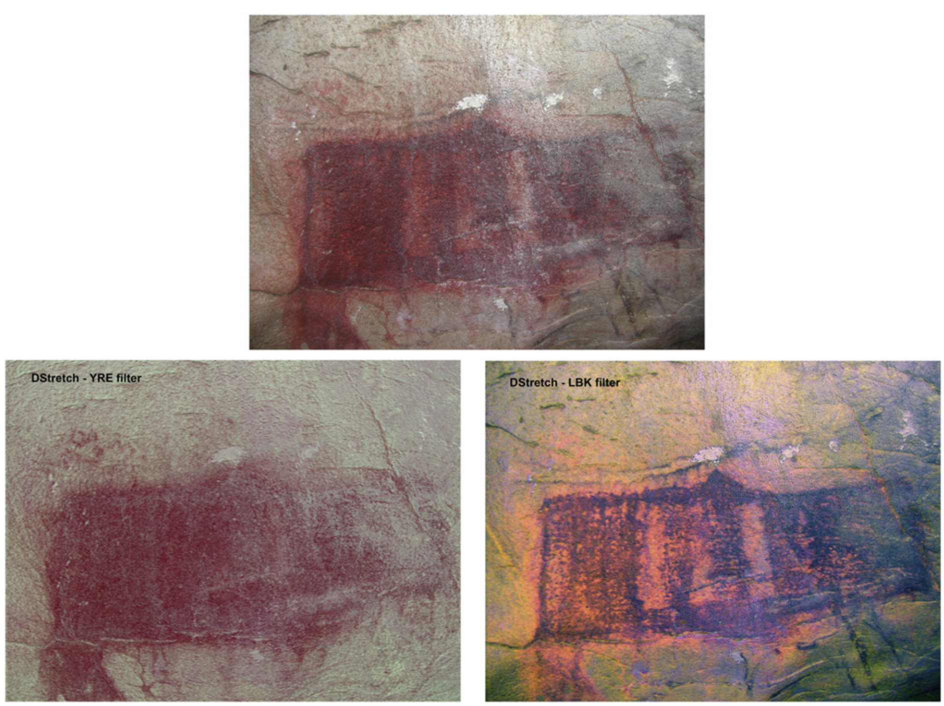

Fig. 6. Application of D-Stretch software on a rectangular graphic sign from Castillo Cave: photography, view of black drawing (filter lbk), view of red color (filter yre).
(Docs. E. Robert)

parts of light spectrum. Additionally, they are not necessarily efficient if the painted figures do not contain organic elements.

Digital photography permits the computing treatment of faded color images. We want here to highlight the application of the plug-in D-Stretch from Image J® program to the study of cave art: “D-Stretch performs a decorrelation stretch on color images. This can enhance faint colors in the image” (extract from the presentation of software by Jon Harman, who developed the plug-in). This software modifies the colorimetric parameters of the TSL (Tint, Saturation and Luminance) color space. The process involves with differential treatments of the colorimetric values of each pixel, based on predictable configured filters. It emphasizes a specific color-cast on the painting which is registered by the camera.

Best results are produced with uniform lighting of the surface (such as a well-positioned and efficient flash or powerful LED panels) with no shadow. We provide as an example a red sign from Blanchard cave that has almost entirely disappeared from view with the naked eye (Fig. 5). With the pre-parameter filter LRE, we can identify its form and observe it in much greater detail.

The application of this digital imagery software facilitates a real process of “virtual reconstruction” of faded paintings. This process was developed in cave in the ANR MADAPCA program, especially with D. Vigears (C2RMF). As mentioned above, this tool has been widely used in rock-art research in open-air contexts (Le Quellec et al., 2013; Le Quellec et al., 2015; Cerrillo-Cuenca and Sepulveda, 2015), and it is now proving invaluable to the recognition and interpretation of paintings in cave environments.

The treatment of a bicolor sign (red and black) from the cave of El Castillo (Cantabria, Spain) with two D-Stretch filters reveals an internal structure and a differentiated utilization of the two colors, which is not visible to the naked eye. The structure of the sign is composed by black lines, and covered over with red pigment (Fig. 6). This is a fairly typical example of the kind of valuable information that we can get from this digital method.

Furthermore, in Font-de-Gaume Cave, during the collective research program “Archéologie des grottes ornées” (dir. C. Cretin), a recent application of D-Stretch settings on a tectiform sign, located in the *Galerie latérale,* revealed a very complete form whereas its appearance. This sign was first considered as a “hémitectiforme” or “semitectiforme” (Capitan et al., 1910; Vialou and Vilhena-Vialou, 2014), as we can observe on H. Breuil's survey renderings (Fig. 7a). The use of the CRGB filter from D-Stretch emphasizes red traces under the calcite, which seems to be located on the left part of the sign (Fig. 7c). We can see a vertical line at the left border and almost 6 horizontal or sub-horizontal lines associated with the right part of the tectiform. Because of this new digital tool, it seems to be complete and to fall into the established category of pentagonal tectiforms of Font-de-Gaume Cave.

Fig. 8. Photography of entity G08, initially interpreted as a bear.
(Photo E. Robert)

Fig. 9. 3D modeling of entity G08, photogrammetry (Photoscan), flat colored at top, flat lines shadow appearance at bottom, Meshlab.
(Docs. E. Robert, S. Petrognani)

3.3. Macrophotography

Macrophotography allows detailed digital imaging of very small subjects. With proper equipment, these images can also be of a very high resolution. A dedicated macro camera lens is specifically designed

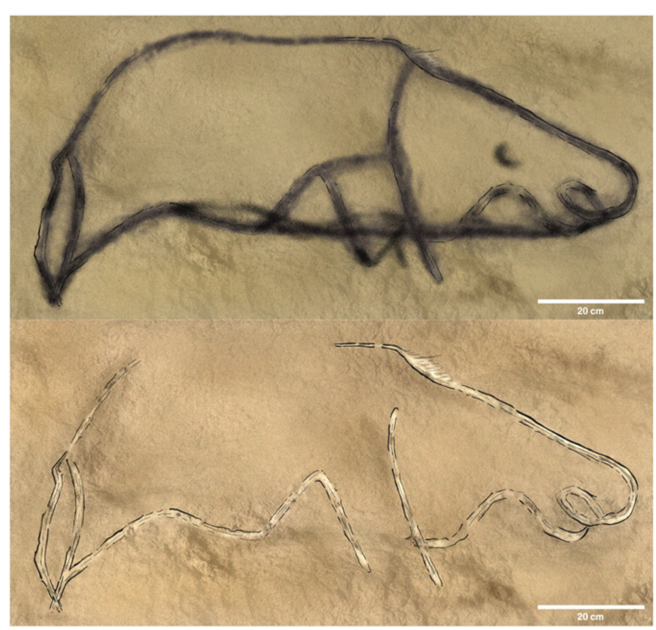

Fig. 10. Engraved Lion G08, top: survey image with transcription of drawings and black soot-marks; bottom: survey image showing only old engravings.
(Docs. S. Petrognani)

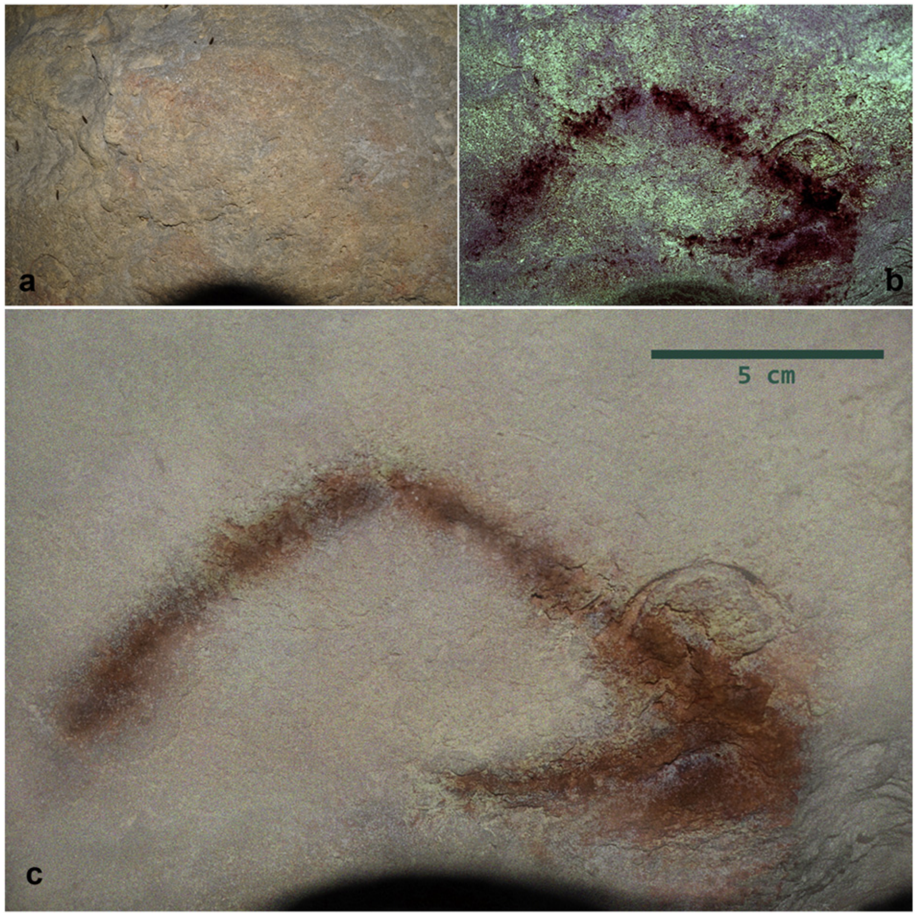

Fig. 11. Right wall red paintings D01 (a: untreated photograph, b: YRE D-Stretch filter, c: infographic reconstitution). (Docs. S. Petrognani, E. Robert)

for this purpose and performs far better than a classic lens positioned near a subject.

As in regular photography, it is necessary to select parameters appropriate for the production of high-quality macrophotographs. Aperture settings determine the amount of light captured by the sensor, and regulates the depth of field, whose optimal quality is often reached between F: 8 and F: 11. This specific photography technique is very efficient for microanalysis of representations, particularly the study of technical phenomena such as engraving gestures and their orientation within figures. For the study of mobiliary art, a range of laboratory equipment can be used to analyze such production traces. In the context of caves, which place certain constraints on the equipment that can be used (see above), photography, and especially macrophotography, provides a method for detailed digital imaging for the study of precise details in cave art, such as in our study of the engravings in Bernoux Cave (see below).

4. Combined use of digital tools and techniques: the study case of Bernoux Cave (Dordogne)

The analyses conducted in Bernoux Cave since 2011 illustrate the great potential of these tools and treatments used in combination.

The cave is located in the north of Dordogne, in the Aquitaine region of France. It was known from 1932 as a strictly engraved cave with a modest corpus of representations. Repeated surveys and analyses with digital photographic tools has recently allowed for the identification of new figures (Petrognani et al., 2014; Robert et al., 2015).

Photography, photogrammetry, macrophotography and decorrelation stretch have been used to:

- Contextualize the representations on the complex surfaces of the cave walls

Fig. 12. Declination of different filters used from the same photography (normal; CRGB; LAB; LRD; LRE). (Docs. E. Lesvignes)

- Enable the reading, decryption, verification and more precise interpretation of several representations
- Detect and record altered or obscured paintings that were previously unknown
- Analyze the technical process used to create the engravings in different parts of the cave.

Each of the techniques has been crucial to our study in all of these areas.

One representation in particular illustrates the benefit of using these techniques in combination: graphic entity G08. It is an animal figure identified as a bear by the researchers who have studied the cave (Peyrony, 1932; Delluc and Delluc, 1979). This interpretation is based essentially on the corpulent aspect of the animal, reproduced in previous surveys, but the reading is complicated by contemporary black markings (probably soot from torches) and by an oblique angle of observation imposed by the cave morphology (Fig. 8). The use of photogrammetry and macrophotography in the reanalysis of this image led us to propose a new interpretation of this representation.

The photogrammetry of the panel was realised with oblique lightning (2 cobra flashes from either side of the engraving, with Nikon Cobra SB-900), then with front lighting, because of the irregular shapes of the wall. Morphological constraints of the cave forced us to use 18 mm lens (F: 8 1/125e). Two software programs were used to create 3D models. The first was 123D Catch® (Autodesk), which provides automatic treatment of photographs to create 3D models. The preliminary results were not very precise, so we used Photoscan® (Agisoft), with better results, especially because there is no resampling of the points of the cloud. Resolution stay light, above millimeter, because of the constraints that the cave morphology places on camera position, and therefore the focal length.

However, the 3D image produced by photogrammetry, without the texture and color, allowed us to reconstruct the outline of the forms without the layer of soot that obscured them visually. The 3D model also offered a complete rendering of the figure, without distortion of the shape. The animal appears thinner compared to the early renderings (Fig. 9). Moreover, the principal lines of the animal, namely those connecting the belly and the foreleg, are clearly more evident.

As it was not possible to obtain all of the information we desired on the lines with photogrammetry alone, we added a series of macrophotographs to the analysis, which allowed us to make a clear distinction between engraved Paleolithic lines and more recent marks. Some lines present very small “grooves” (traces of the tool) inside the engraving and confirm a Paleolithic origin. On the contrary, the macrophotography reveals, at the base of the head, some tiny details, superimposed on the original line, which have a more recent origin. We therefore excluded them from the analysis of the Paleolithic image.

The combined results of these two techniques suggest another interpretation of the figure: not as a bear, but as a feline. This interpretation is based primarily on the new reading of the head (Fig. 10), due to the

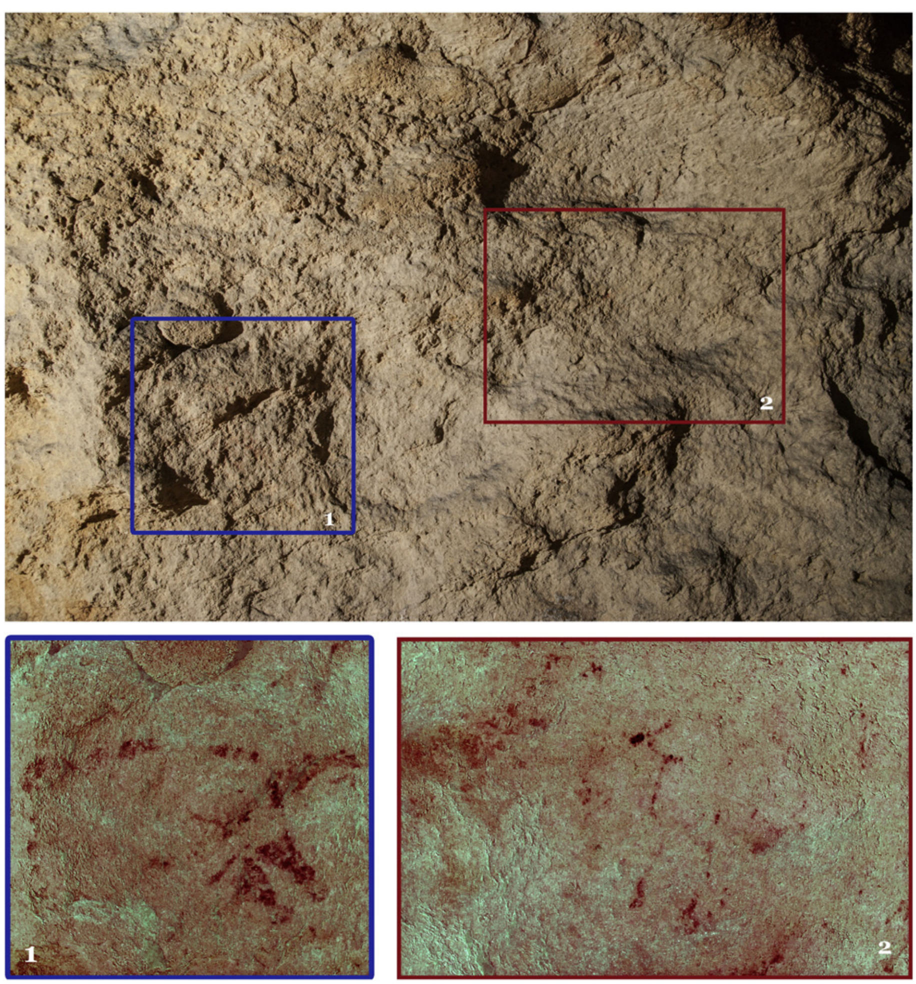

Fig. 13. Left wall red paintings G09: top: photograph, 1: YRE filter, red mammoth, 2: YRE filter, red tracing. (Docs. E. Lesvignes)

correction of the proportions provided by the 3D treatment, and to the distinction between Paleolithic engraved lines and traces of more recent origin.

The use of color-enhancement tools was also of great utility at Bernoux Cave and revealed no fewer than seven new representations. At the beginning, we were able to see a few red traces on the right wall of the cave. The YRE filter in D-Stretch was applied to highlight the shades of red. We found series of red points and lines, and a possible sign or schematic animal head (Petrognani et al., 2014). After the initial identification of these forms, we manually selected in Photoshop® the pigment surfaces and further defined the borders and density of the pigmented areas. We finished by a graphic survey following the process of "virtual reconstruction" (Fig. 11).

After this discovery, we made a visual survey of the whole gallery. The photographic shooting and post-processing was conducted by one of us (E. Lesvignes) with the use of several colorimetric D-Stretch filters: CRGB, LAB, LRD and LRE (Fig. 12). Photographs were taken with a cobra flash tool in order to ensure the uniform illumination of the surface and stability of the light source necessary for acquiring reliable informative from each image. A zone on the left wall about two meters long showed potential for a series of close-up photos in the form of a "photographic survey" of the whole surface in order to verify the presence of pigment traces. On this left part of the wall, the deposits of red pigment appear fainter, almost invisible. As before, image treatment was performed with D-Stretch filters; some of them obtained more efficient results than others.

By stressing different dominant shades, strong colorimetric contrasts were established. They enabled a more precise reading of the represented subject. This technique also allowed us to distinguish the pigments that make up the drawings from natural traces of ochre, with the help of LAB filter, which can differentiate between two kinds of red: one that is more purple and another that is more orange. On this basis, we managed to identify different sets of features (Fig. 13) with a colorimetric intensity almost identical to that of one of the first paintings identified on the right wall.

Among the lines detected with this method, one clearly defined representation appeared (Fig. 13, frame 1). In order to increase the precision of our analysis, new images of RVB photography were executed closer to the wall. Other organized red lines were revealed near the most recently-discovered painted area. Visual information and infographic observations with CRGB and LAB filters allowed us to identify two red mammoths painted on the inferior part of the wall (Fig. 14).

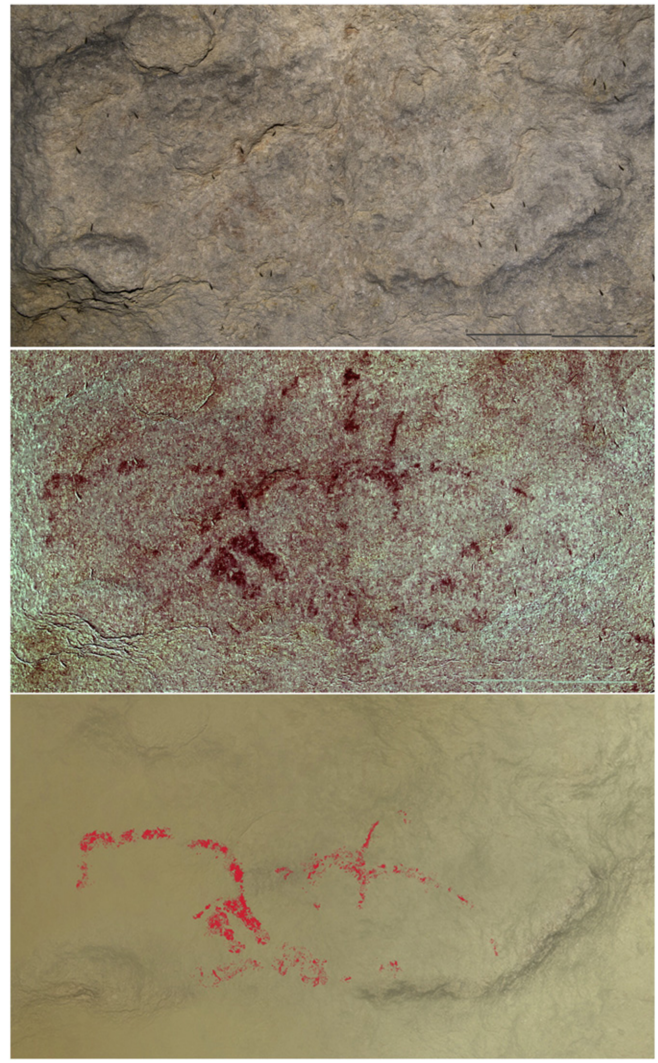

Fig. 14. Paintings G09-1: two small mammoths (photography, YRE D-Stretch filter, infographic reconstitution).
(Docs. E. Lesvignes, S. Petrognani)

This reading is based on several distinctive anatomical elements: a "bun" (French: *chignon*) at the top of the head and a hollow of the neck for the first mammoth (G09-1), and a hollow of the neck on the profile of the second mammoth (G09-2). On the right of this second figure, the vertical lines appear as a graphic entity with two principal edges (Fig. 13, frame 2). Unfortunately, these traces are almost completely erased and not clear enough for the proposal of a specific interpretation.

Additionally, macrophotography applied at Bernoux Cave with the following results:

First of all, it enables us to distinguish between two kinds of engravings. The first is a large type of engraving, used in the primary part of the cave, particularly in the panel at the entrance, which represents three mammoths, a rhinoceros and a feline. The lines that form these engravings all have the same type of profile, large and flared, but without technical traces of the tool in the profile, certainly because of the alteration process.

The second type of engraving, located in the center of the cave, is narrower and thinner in profile. With the help of macrophotography, we were able to more closely examine the edges of these lines and the groove inside them, as shown in the graphic entity G13. Macrophotography was conducted on two segments of the same line. We managed to identify the point of origin where the artist began engraving (Fig. 15), to understand the direction of the engraving action (from the top downward) and to reconstitute the path of the line with interruptions due to holes in the wall. For this imaging process, we used the Nikon D80 camera with 70 mm lens (f: 4.5 - 1/160).

This approach allowed us to differentiate between markings of natural and artificial origin, and to decide which ones to consider components of symbolic compositions, especially in the case of a specific sector of the right wall (entity D04). This entity is narrower compared to others, and does not contain any internal technical traces. It is very difficult to identify because similar-looking natural cracks are present on the same wall. Thus, the macrophotography is essential for comparing engravings and natural cracks at a high resolution in order to document and properly identify them. Four sectors were selected, two corresponding to possible engravings and two others to probable cracks. We used the same camera (Nikon D80 with 70 mm lens) with the following parameters: F: 8 - 1/100. On photographs, one can distinguish the irregular edges and depth of the cracks, on one hand (Fig. 16a and c), and the square edges (Fig. 16b) or curved edges (Fig. 16d) that form the borders of the engravings, on the other. In the end, we were able to identify the hindquarters of an animal of undetermined species (Fig. 17).

Thus, the studies described here in Bernoux Cave illustrate the potential of the combined scientific application of several digital

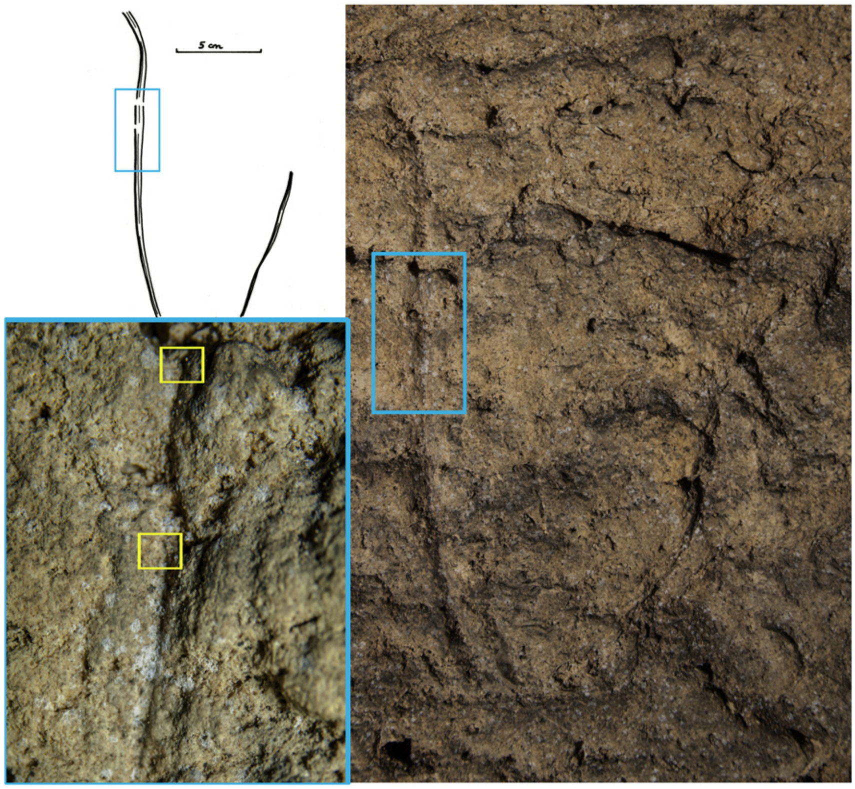

Fig. 15. Entity G13 of les Bernoux. At right, photographs (E. Lesvignes). At top left, survey of engraving (C. Lucas, E. Robert). At bottom left, macrophotography of the segment of engraving. We can identify the points where the engraving begin and continue after interruption (in yellow rectangles).

photographic tools that present a diverse possibilities for the recording and analysis of art in subterranean environments.

5. Conclusion

In the end, each of these digital photographic techniques contributes to new results for the study of Paleolithic cave art, and they are more efficient when they're applied in combination. We have presented here some specific methods in enough detail, that they can be applied and adapted in different context, in the hope that these methods will continue to improve.

3D digitization is not only useful for recording the morphology of caves or reconstituting the context of parietal images. It is also essential for reading and interpreting certain figures. Photogrammetry presents a significant method for enriching archaeological information and furthering the goals of conservation efforts (Lesvignes, 2015).

Likewise, decorrelation stretch treatment offers significant potential in terms of new discoveries, in particular for visualization and conservation challenges presented by the alteration of pigments in painted caves. Digital approaches are much more appropriate to cave environments than many other techniques commonly used in laboratory settings or even in the study of open-air rock art, in part to the uneven and often challenging constraints of space that caves present. In all decorated caves, researchers can now make observations and readings of altered paintings, and precise structures and borders of traces or figurative representations, as shown in our examples from the caves of El Castillo, Font-de-Gaume and Bernoux. In the case of the last example, photographic surveys on the wall with a D-Stretch plugin have revealed the presence of color in the cave, and previously unknown paintings of mammoth.

Finally, macrophotography is necessary for the recognition and technical analysis of engravings. In Bernoux Cave, we were able to more closely assess profiles of technical traces, such as drawing gestures, and to distinguish certain engravings with lines that were more ambiguous without the aid of high-resolution images. The microscopic approach needs to be further developed to recover precise and small-scale information from engravings. It may eventually present great possibilities for rock art traceology, as it has in the case of portable art. Current work is presenting promising new methodological paths in these areas (Plisson, 2014; Plisson and Zotkina, 2015).

The implementation of different methods of photography and related tools represents a clear benefit to cave-art research. New applications should be built in collaboration between archaeologists and engineers to respond to current challenges in the study of portable and cave art.

Applications already under development for cave art include three-dimensional reconstruction of the representations, surveys on 3D models, and the application of GIS in decorated caves. These have been applied already in certain caves, such as Chauvet (Ardèche) (Boche et al., 2012) and Cussac (Dordogne) (Feruglio et al., 2015) and are still under development in others (Robert et al., 2014b). These applications will undoubtedly offer new discoveries and new methodologies for the study of symbolic productions in prehistory.

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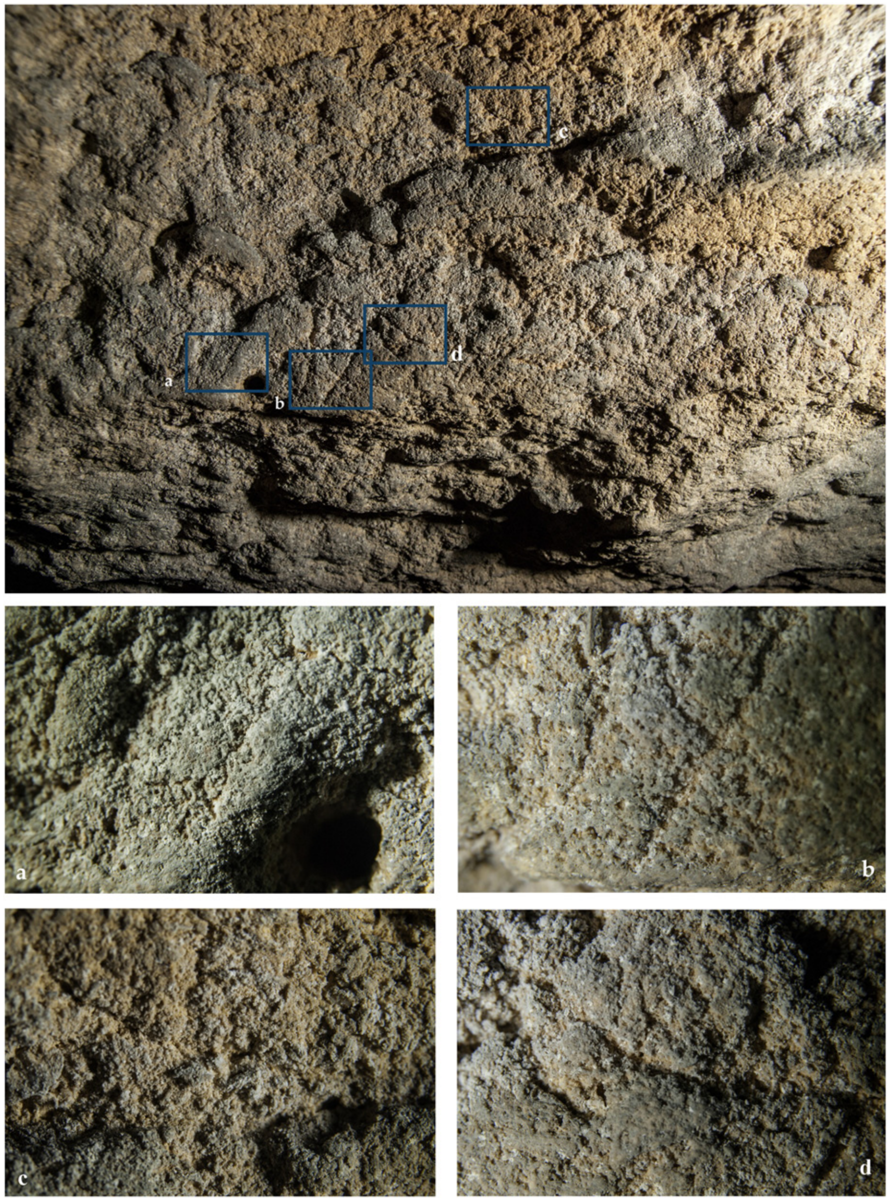

Fig. 16. Macrophotography on D04 entity. Top: photograph, a: macrophoto of a natural crack, b: macrophoto of engravings, c: macrophoto of naturals cracks, d: macrophoto of engraving. (Docs. E. Lesvignes)

Fig. 17. Survey of D04 entity, undetermined hindquarters animal. (Docs. E. Robert, E. Lesvignes)

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References

Azema, M., Gely, B., Bourrillon, R., Lhomme, D., 2013. La grotte ornée paléolithique de Baume Latrone (Gard, France): la 3D remonte le temps. Palethnologie n°5, 244–246.

Bello, S.M., De Groote, I., Delbarre, G., 2013. Application of 3-dimensional microscopy and micro-CT scanning to the analysis of Magdalenian portable art on bone and antler. J. Archaeol. Sci. 40-5, 2464–2476.

Boche, E., Monney, J., Ployon, E., Sadier, B., Delannoy, J.-J., Geneste, J.-M., Jaillet, S., 2012. Le SIG comme outil fédérateur de la recherche interdisciplinaire: application à la grotte Chauvet-Pont d'Arc. Actes du colloque des «Journées informatiques et archéologie de Paris». Archeologia e calcolatori Vol. Suppl. 3, pp. 97–112.

Burens, A., Grussenmeyer, P., Guillemin, S., Carozza, L., Bourrillon, R., Petrognani, S., 2011. Numérisation 3D de la grotte des Fraux (Saint-Martin-de-Fressengeas, Dordogne, France): approche multiscalaire. In: S. Jaillet, E. Ployon, T. Villemin (Éds.), Images et modèles 3D en milieux naturels. Chambery: Edytem, université de Savoie, pp. 183–190, (Collection Edytem, n° 12).
Capitan, L., Breuil, H., Peyrony, D., 1910. La caverne de Font de Gaume. Impr. le Chêne, Monaco 271 pp., 244 fig., LXV pl. h-t.
Cerrillo-Cuenca, E., Sepúlveda, M., 2015. An assessment of methods for the digital enhancement of rock paintings: the rock art from the precordillera of Arica (Chile) as a case study. J. Archaeol. Sci. 55, 197–208.
David, S., Pigeaud, R., Robert, E., Petrognani, S., D'Errico, F., Bereiziat, G., Cailhol, D., Griggo, C., Jaillet, S., Jeannet, M., Paitier, H., 2014. Un site inédit à l'interface de territoires symboliques du Paléolithique supérieur ancien: la grotte des Gorges (Jura). In: Otte, M., Le Brun-Ricalens, F. (dir.), Modes de déplacements et de contacts dans le Paléolithique eurasiatique, ERAUL n°140 et Musée luxembourgeois n°5, Liège et Luxembourg, Actes du colloque de Liège 2012, pp. 537–567, (20 fig).
Delannoy, J.-J., Sadier, B., Jaillet, S., Ployon, E., Geneste, J.-M., 2010. Reconstitution de l'entrée préhistorique de la grotte Chauvet-Pont d'Arc (Ardèche, France): les apports de l'analyse géomorphologique et de la modélisation 3D. Karstologia 56, 17–34 2010.
Delluc, B., Delluc, G., 1979. La grotte ornée des Bernous à Bourdeilles (Dordogne). Bull. Soc. Préhistorique Française 76 (-2), 39–45.
D'Errico, F., 1994. L'art gravé Azilien: de la technique à la signification, Gallia Prehistoire. CNRS Ed, Paris 329 pp.: ill.
Egels, Y., 2011. La photogrammétrie, principes généraux et terminologie. In: S. Jaillet, E. Ployon, T. Villemin (Éd.), Images et modèles 3D en milieux naturels. Chambéry: Edytem, université de Savoie, p. 41–50, (Collection Edytem, n° 12).
Feruglio, V., Dutailly, B., Ballade, M., Bourdier, C., Ferrier, C., Konik, S., Lacanette–Puyo, D., Mora, P., Vergnieux, R., Jaubert, J., 2015. Un outil de relevés 3D partagé en ligne: premières applications pour l'art et la taphonomie des parois ornées de la grotte de Cussac (ArTaPOC/programme LaScArBx). In: Vergnieux, R., Delevoie, C. (Eds.), Virtual Retrospect 2013Coll. Archeovision Vol. 6. Ausonius Ed, pp. 49–56.
Fredlund, E.G., Sundstrom, L., 2007. Digital infra-red photography for recording painted rock art. Antinquity 81 (313), 733–742.
Fritz, C., 1999. La gravure dans l'art mobilier magdalénien. Du geste à la représentation. Documents d'Archéologie Française (D.A.F.) Vol. n°75. Maison des Sciences de l'Homme, Paris 217 p., éd.
Fritz, C., Tosello, G., Perazio, G., Péral, J., Guichard, L., 2010. Technologie 3D et relevé d'art pariétal: une application inédite dans la grotte de Marsoulas. In Situ [En ligne], p. 13 URL: http://insitu.revues.org/6745.
Gunn, R.G., Ogleby, C.L., Lee, D., Whear, R.L., 2010. A method to visually rationalise superimposed pigment motifs. Rock Art Res. 27–2.
Le Quellec, J.-L., Harman, J., Defrasne, C.l., Duquesnoy, F., 2013. D-Stretch® et l'amélioration des images numériques: applications à l'archéologie des images rupestres. Les Cahiers de l'AARS 16, 177–198.
Le Quellec, J.-L., Duquesnoy, F., Defrasne, C., 2015. Digital image enhancement with DStretch: is complexity always necessary for efficiency? Digital Applications in Archaeology and Cultural Heritage
Lesvignes, E., 2015. Usages et apports de la photographie en archéologie. Archéo Situla, Bulletin annuel du Cedarc, Musée du Malgré-Tout, pp. 3–32.
Lorblanchet, M., 1981. Les dessins noirs du Pech Merle. Congrès Préhistorique du Pech Merle, Quercy, 1979, pp. 178–207 22 fig., 3 tabl., biblio.
Man-Estier, E., Deneuve, E., Paillet, P., Loiseau, L., Cretin, C., 2015. Du nouveau aux Combarelles I (Les Eyzies-de-Tayac, Dordogne, France). PALEO 26, 201–214.
McDonald, J., Steelman, K.L., Veth, P., Mackey, J., Loewen, J., Thurber, C.R., Guilderson, T.P., 2014. Results from the first intensive dating program for pigment art in the Australian arid zone: insights into recent social complexity. J. Archaeol. Sci. 46, 195–204.
Mélard, M., 2010. L'étude microtopographique et la visualisation 3D dans l'analyse de gravures préhistoriques – L'exemple des pierres gravées de La Marche. Situ [En ligne] 13 | 2010, 8 fig URL: http://insitu.revues.org/6837.
Paillet, P. dir., 2014. Les arts de la Préhistoire: micro-analyses, mises en contextes et conservation, PALEO n°spécial, (366 pp.).
Pastoors, A., Weniger, G.C., 2011. Cave art in context: methods for the analysis of the spatial organization of cave sites. J. Archaeol. Res. 19-4, 377–400.
Petrognani, S., Robert, E., Boche, E., Cailhol, D., Lucas, C., Lesvignes, E., 2014. Au cœur des premières manifestations graphiques du Paléolithique supérieur: Nouvelles découvertes dans la grotte des Bernoux (Dordogne). Bull. Soc. Préhistorique Française tome 111, 3, pp. 413–432, (16 fig).
Peyrony, D., 1932. Les gisements préhistoriques de Bourdeilles (Dordogne). Archives de l'Institut de Paléontologie humaine10, Masson, Paris 95 p.
Pierrot-Deseilligny, M., Cléry, I., 2011. Évolutions récentes en photogrammétrie et modélisation 3D par photo des milieux naturels. In : S. Jaillet, E. Ployon, T. Villemin (Éd.), Images et modèles 3D en milieux naturels. Chambéry: Edytem, université de Savoie, p. 51–66, (Collection Edytem, n° 12).
Pinçon, G., Bourdier, C., Fuentes, O., Abgrall, A., 2010. De la manipulation des images 3D. In: In Situ [En ligne], 13 | URL: http://insitu.revues.org/6814.
Plisson, H., 2014. 3D en kit: des solutions pour la tracéologie et au-delà. Archeologia E Calcolatori, suppl.5, 2014, Rome, pp. 102–116 4 fig.
Plisson, H., Zotkina, L., 2015. From 2D to 3D at macro- and microscopic scale in rock art studies. Digital Applications in Archaeology and Cultural Heritage, pp. 102–119 30 fig., biblio.
Rivero, O., 2011. La noción de aprendizaje en el arte mobiliar del Magdaleniense Medio cántabro-pirenaico: la contribución del análisis microscópico. Trab. Prehist. 68 (2), 275–295.
Robert, E., Pierrot-Deseilligny, M., Vigears, D., Plassard, J., Martin-Beaumont, N., Plassard, F., Egels, Y., 2014a. La photogrammétrie à haute résolution en grotte ornée: numérisation des gravures de Rouffignac et Blanchard. In PALEO n° spécial, Paillet, P. (dir.), Les arts de la Préhistoire: micro-analyses, mises en contextes et conservation, pp. 95–104, (4 fig., biblio).
Robert, E., Egels, Y., Boche, E., Peyroux, M., Vialou, D., Vigears, D., Paillet, P., 2014b. Applications 3D pour la contextualisation et le relevé d'art en grotte ornée. Archeologia E Calcolatori, suppl.5, 2014, Rome, pp. 88–101 5 fig.
Robert E., Petrognani, S., Lesvignes, E., Cailhol, D., Lucas, C., Boche, E., 2015. La grotte des Bernoux (Dordogne, France): un modèle symptomatique de l'art pariétal du début du Paléolithique supérieur? In Corchon, MªS y Menendez, M. ed Cien Años de arte Paleolítico en Asturias Centenario del descubrimeinto de La Peña de Candamo (1914–2014). Ediciones de la Universidad de Salamanca, pp. 73–86, (8 fig).
Ruiz-Redondo, A., González-Sainz, C., Garate-Maidagan, D., 2015. Back to the past: symbolism and archaeology in Altxerri B (Gipuzkoa, Northern Spain). Quat. Int. 1–11. http://dx.doi.org/10.1016/j.quaint.2015.07.013 (in press).
Vialou, D., Vilhena-Vialou, A., 2014. Font-de-Gaume: le site des tectiformes. In PALEO n° spécial, Paillet, P. (dir.), Les arts de la Préhistoire: micro-analyses, mises en contextes et conservation, pp. 219–230, (5 fig., biblio).