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)

Claudia Defrasne, Marion Massé, Manuel Giraud, Bernard Schmitt, Damien Fligiel, Stéphane Le Mouélic, Emilie Chalmin

To cite this version:

Claudia Defrasne, Marion Massé, Manuel Giraud, Bernard Schmitt, Damien Fligiel, et al.. 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). Archaeological and Anthropological Sciences, 2023, 15 (8), pp.116. 10.1007/s12520-023-01812-6 . hal-04293291

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)

Claudia Defrasne[1], Marion Massé[2], Manuel Giraud[2], Bernard Schmitt[3,] Damien Fligiel[4], Stéphane Le Mouélic[2], Emilie Chalmin[1]

[1] EDYTEM, UMR 5204, Université Savoie Mont Blanc, CNRS, 73376 Le Bourget du Lac, France.

[2] LPG, CNRS UMR 6112, Nantes Université, Université d'Angers, Le Mans Université, 44322 Nantes, France

[3] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

[4] OSUNA, CNRS, UAR3281, Nantes, France.

Corresponding author : Claudia Defrasne, claudia.defrasne@univ-smb.fr. ORCID 0000-0002-8775-6702

Abstract

This paper presents a methodological contribution to rock art archaeology by demonstrating the benefits of hyperspectral imaging, a relatively new method, for the understanding of rock art sites. It illustrates the complementarity of VNIR hyperspectral imaging, applied in rare cases to rock archaeology, and SWIR hyperspectral imaging, implemented here in a unprecedented way to a rock art panel. Applied to a schematic rock art site in southern France, the Otello rock shelter (Saint-Rémy-de-Provence, France), this method allowed the discovery of numerous new figures invisible to the naked eye or unsuspected after image enhancement with the DStretch plug-in of the Image J software, the individualisation of figures within complex superpositions as well as the discovery of figures covered by weathering products. Moreover, by conferring a spatial dimension to the analysis of pictorial matter, thus allowing a classification of pigments at the scale of the wall, hyperspectral imaging makes it possible to automatically isolate different paintings and to carry out objective groupings of figures on the basis of their composition. Finally, hyperspectral imaging allows us to precisely document, distinguish and characterise weathering products interacting with painted figures. For all of these reasons, this method appears essential to highlight the relative chronology and syntax of iconography, and consequently to understand its cognitive nature.

Keywords

Schematic rock art, hyperspectral imaging, Neolithic, rock art recording, pigment analysis

Reference

Claudia Defrasne, Marion Masse, Manuel Giraud, Bernard Schmitt, Damien Fligiel, Stéphane Le Mouélic, Emilie Chalmin (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). Archaeological and Athropological Sciences. 15, 116. https://doi.org/10.1007/s12520-023-01812-6

Introduction

We propose in this paper a methodological contribution to rock art archaeology by demonstrating the benefits of hyperspectral imaging for the understanding of rock art sites, their chronology, the graphic and social practices to which they bear witness and the taphonomy of the rock walls. This contribution is part of a desire (i) to make progress in the understanding of Holocene schematic rock art and its syntax ; (ii) to use non-invasive methodologies as much as possible in a research dynamic characterised by the implementation of integrated/interdisciplinary studies of Holocene schematic rock art, including archaeology, geomorphological studies, physico-chemical characterisation of colouring matter, and also pragmatic and cognitive semiotics of visual culture (Defrasne et al., 2019a, 2021).

Holocene schematic rock art constitutes one of the largest corpus of European prehistoric rock art. It is present in all the northern fringes of the Mediterranean (Hameau 2002; Martinez Garcia and Hernandez Perez 2013; Nicoud et al. 2022). However, it is the Iberian Peninsula and Mediterranean France that have the greatest number of occurrences to date. In France, Neolithic schematic rock art (Ve - IIIe mill. BC) remains little studied, largely unknown and often kept away from the reconstructions of prehistoric societies (Hameau 2002; Defrasne et al. 2019). This rock art is composed of a repertory of recurring forms reduced to their simplest expression, mostly painted, and is present in the open air as well as underground. All the sites share both environmental and iconographic characteristics. We therefore assume that this corpus is able (i) to shed additional light on Neolithic societies and the spatial distribution of their cultural components; (ii) to participate in the modelling of intra- and extra-regional cultural interactions. In this perspective, schematic rock art constitutes a new way of approaching Neolithic societies and provides a complementary contribution to their understanding, through the study of communication and transmission of practices and collective representations across cultural boundaries and their regional re-appropriations. One of the scientific challenges is therefore to characterise the cognitive nature of the Neolithic schematic rock art in order to question (i) the associated social practices and uses; (ii) its role in Neolithic societies. Can we really speak of schematism and what does it imply from a cognitive point of view? Why did prehistoric societies use *schematism*, instead of figurative imagery, in certain selected places of their environment? What are the implications in anthropological and cultural terms? To reach such an aim, it is essential to understand the syntax and construction of this rock art. However, such an objective comes up against a double difficulty that is related to the study of past societies: (i) the disappearance of the social and cultural context surrounding the graphic practice and (ii) the presence of multiple temporalities on a wall that today may give the impression of a homogeneous whole and (iii) the presence of empty spaces that need to be confirmed and/or characterised. These difficulties are reinforced by the fact that the mineral matter does not allow direct dating. This is why it is necessary to implement a rigorous methodology to dissociate and characterise these different temporalities and to understand the logic of the construction of graphic systems.

The characterisation of colouring matter and its spatial distribution at the wall scale is an essential step in achieving these objectives. This contributes to a better understanding of (i) the syntax of the graphic systems by grouping figures on the basis of their composition; (ii) their relative chronology (micro-stratigraphies) and (iii) the associated practices (provenance of colouring matter and their evolution, preparation of pictorial matter, repainting of figures). This should be done in close connection with the geomorphological study of the sites to link the taphonomy of the walls (nature and location of the weathering crusts, alterations, etc.) to the overall evolution of the shelter. Through this article, we will show that the contribution of hyperspectral imaging is essential since it allows : (i) to identify painted figures invisible to the naked eye and in RGB, even after image enhancement with image decorrelation software like Image J coupled with the plug-in DStretch (Le Quellec et al. 2013, 2015; Defrasne 2014); (ii) to distinguish figures integrated into superimpositions that image enhancement with DStretch had not allowed to separate; (iii) to differentiate pictorial matter that, to the naked eye, did not present any colour variability; (iv) to group figures on the basis of their composition and (iv) to map the mineralogy of the substrate and weathering products. Hyperspectral imaging is consequently at the interface of the different disciplines, allowing the realisation of a precise and exhaustive tracing of the painted figures, as well as a cartography of the composition of the colouring matter and of the wall alterations.

I. Hyperspectral imaging: principle and applications

A. Method

Hyperspectral imaging is a non-destructive measurement technique that allows us to take hundreds of photographs of the same area at different contiguous wavelengths. For each pixel in a hyperspectral image, we have a full visible-near infrared spectrum that may potentially allow us to trace the composition and physical state of the surface contained in this pixel. The analysis of all pixels can then lead to a mapping of the composition over the whole image or painted composition. Hyperspectral imaging allows the simultaneous acquisition of spectral and spatial information into a single 3D data cube (Borengasser et al. 2007).

Hyperspectral cameras are commonly used in the exploration of the Earth's surface and other planetary bodies (Moon, Mars, Mercury, Titan, Pluto, etc.) in space or airborne form (e.g. Gabasova et al. 2021, Le Mouélic et al., 2018, Massé et al., 2012). This technique is used in many applications such as geosciences, the study of vegetation, hydrology, the study of urban environments or coastal ecosystems (e.g. Frati et al., 2021). In the field of geosciences, it allows the characterisation and mapping of the mineralogical composition of the surface. This is fundamental for the identification of geological structures and associated formation environments, in order to trace the geological history of the region (e.g. Peyghambari et al., 2021). These measurements can be carried out on a regular basis to monitor time and analyse possible surface changes. Hyperspectral imaging has also been strongly developed in many other areas such as food inspection, forensic science, medical surgery and diagnosis, and military applications (e.g. Khan et al. 2018).

B. Hyperspectral imaging in heritage studies

Hyperspectral imaging is now widely used in heritage studies and art history, for the study of easel paintings, manuscripts, wall paintings, objects or precious stones... The study of ancient pigments and painting skills constitutes the major part of the published research. The different pigments used, often of mineral origin for old paintings, can be revealed by Vis-NIR-SWIR spectroscopy. Hyperspectral imaging can be used to map the distribution of pigments and inks, to characterise them, to identify binders, to identify techniques, to visualise overlaid sketches or the outlines of figures and to study palimpsests (Fischer and Kakoulli 2006; Kim and Rushmeier 2011; Le Mouélic et al. 2013; Daniel and Mounier 2015; Cucci et al. 2016, 2019; Daniel et al. 2017; Mulholland et al. 2017; Daveri et al. 2018; de Viguerie et al. 2020; Li et al. 2020). In archaeology, hyperspectral imaging has been used to study the polychromy and map the distribution of pictorial matter of Greek sculpted friezes, Egyptian tombs and Roman buildings, to map alteration processes and to enhance vanishing traits (Alfeld et al. 2018, 2019; Cucci et al. 2020; Cortea et al. 2021). It should be noted that it is also sometimes used in the monitoring of works of art, to map corrosions or other alterations or former interventions carried out in the framework of restoration campaigns (Liang 2012; Catelli et al. 2018; Sandak et al. 2021).

C. Hyperspectral imaging in rock art studies

The “reading” of the decorated walls is often made difficult by the alterations they have undergone, which have partially or totally erased the rock art. The advent of digital technologies has thus allowed the use of image enhancement software for the last twenty years, and in particular the use of the DStretch plug-in of the Image J software (Harman 2005; Quesada Martínez 2008; Le Quellec et al. 2013, 2015; Domingo et al. 2013). This software uses the decorrelation stretch algorithm, an image enhancement technique first used on aerial photos, and highlighting colour differences that are barely visible to the naked eyes. Statistical processing allows the colour histogram to be stretched. DStretch is one of the most efficient tools to decipher faint paintings while being cheap, fast and easy to use. However, it is sometimes insufficient, especially as the processed photos have been recorded in RGB to match human vision. It is therefore necessary to record scenes with an instrument covering the electromagnetic spectrum beyond and more finely than the three wide spectral channels (RGB) of standard colour cameras. This is the role of hyperspectral imaging.

Despite its notable contributions in heritage studies, its use in rock art archaeology is very recent and still almost non-existent, mostly developed by a single group (Bayarri et al. 2015, 2016, 2019, 2021; Bayarri Cayón 2020; Ripoll et al. 2021). This is probably due to the difficulties of outdoor implementation of hyperspectral instruments in challenging places such as caves and rock shelters, and on large decorated rock surfaces. Such conditions make it difficult to acquire images that meet the requirements of uniform illumination conditions and minimisation of optical and geometrical deformations (Alexopoulou et al. 2019). However, the very characteristics of the rock art and the walls that support it (pictorial matter with different mineralogical compositions, different colours and textures, overlaying of figures by weathering crusts, superimpositions of figures) suggest a significant potential of hyperspectral imaging applied to rock art sites (Bayarri et al. 2021) (Schmitt et al. 2022). Indeed, the few published studies testify to the ability of the method to distinguish and characterise the different pictorial matters used, to reveal the calcite-covered figures, to study the state of conservation of the wall and to analyse the technical processes. This makes it possible to complete the graphic compositions and increase our knowledge of the decorated walls and their relative chronology (Bayarri et al. 2019, 2021).

We propose here to test hyperspectral imaging on a rock shelter with a very abundant iconography characterised by numerous superimpositions, within which it is often difficult to distinguish the figures, as well as by numerous weathering crusts. We also propose to extend the spectral domain of hyperspectral imagery to the 400-2500 nm range by coupling VNIR+SWIR field spectroradiometer. Previous studies by Bayarri et al. only used a VNIR hyperspectral imager (covering the 400-1000 nm range) complemented with ‘point’ measurements with a VNIR+SWIR field spectroradiometer and sometimes with a 5-band multispectral imager working in the SWIR and LWIR/MIR ranges (1-5 µm) (Bayarri Cayón 2020).

Hyperspectral imaging is used here at several levels of the integrated study of the Otello rock shelter: (i) as an aid to the recording of the whole of the preserved iconography; (ii) in the analysis of the pictorial matter, their chronological succession and spatial distribution, as well as the wall conditions.

II. Hyperspectral imaging at the Otello schematic rock art site:

A. Description of the site

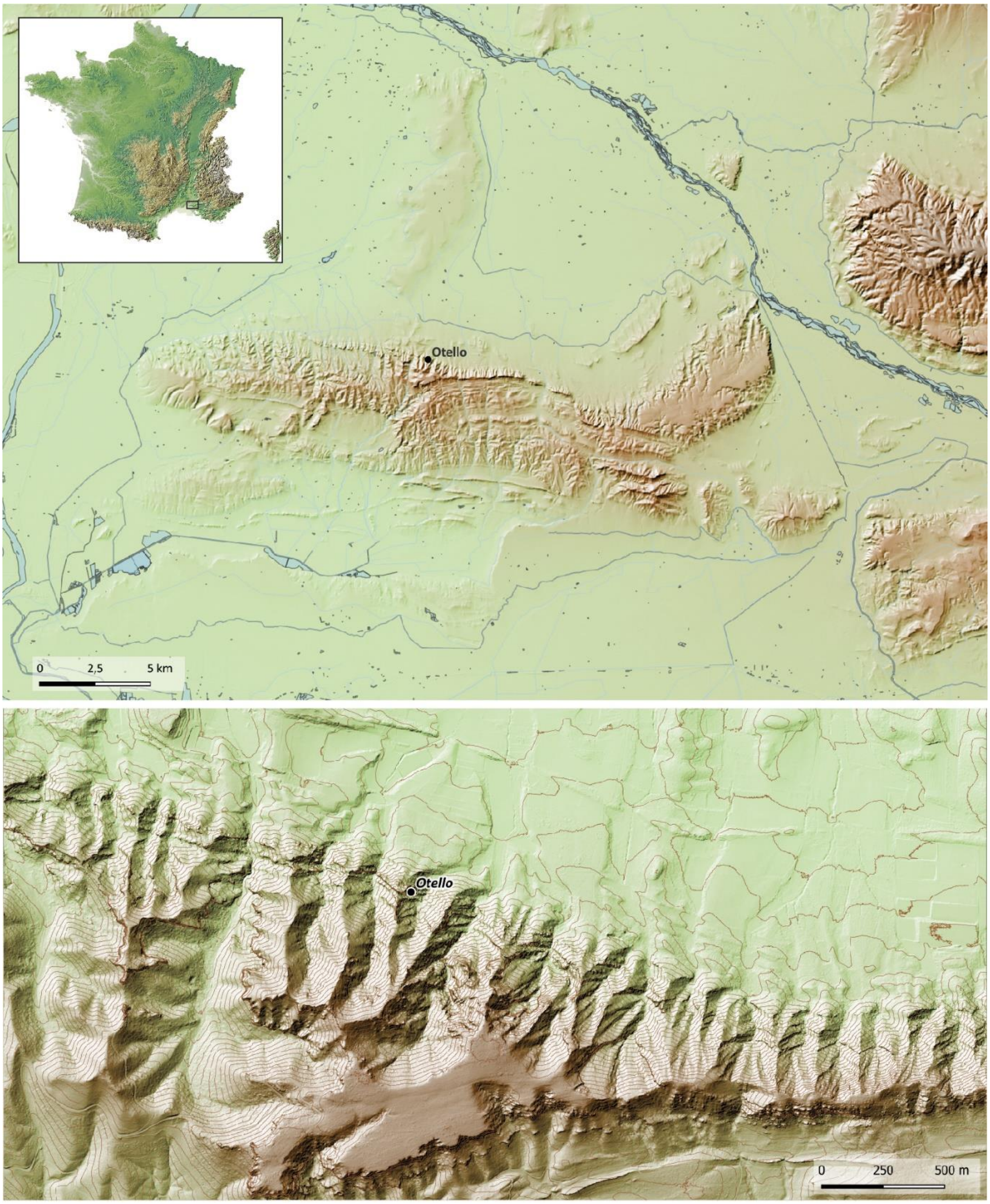


Fig. 1 Location of the Otello rock art site in France and in the Alpilles mountain range (DMS coordinates of the closest modern town: 43°47’22.37”; 4°49’56.99”. CAD: C. Defrasne).

Discovered in 2005, the Otello rock shelter is located on the southern flank of a prominent rocky ridge on the northern slopes of the Alpilles massif (Fig. 1 and 2). It thus offers an unobstructed view over the plain of Saint-Rémy-de-Provence (Bouches-du-Rhône, France).

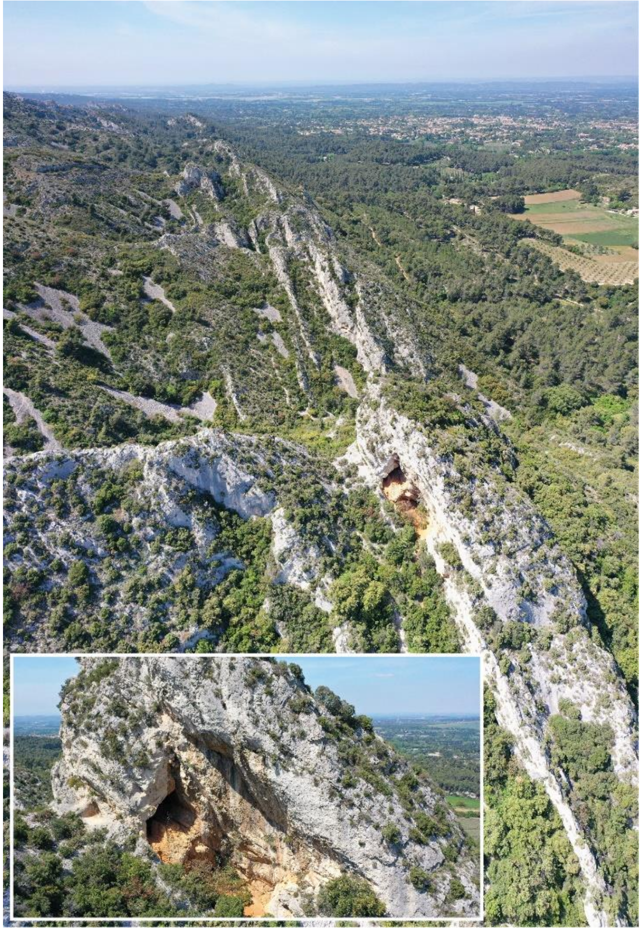


Fig. 2 Location of the Otello rock shelter in the northern rocky ridge of the Alpilles mountain range (photo : S. Jaillet)

It has a particular architecture composed of different spaces: an esplanade surrounded by rock (lower shelter, 13 x 8m) and a large covered shelter located 8 m above the first and itself consisting of a small corridor (5 x 1.50 m) separated from a large room of 12 x 3 m by a rocky step (Hameau 2011). The passage from the lower shelter to the upper shelter is via a steep and narrow rocky ramp. The upper shelter is entirely covered. It is bordered to the north by a fault plane forming a continuous 8m long panel, on which the majority of the paintings are preserved (Fig. 3). This wall, inclined at 28°, with numerous weathering crusts formed before or after the paintings, is white at the bottom of the shelter, black in the middle part, lightening towards the porch until it has the yellow tint of the limestone. Two campaigns of recording of the rock paintings were carried out by Ph. Hameau in 2006 and 2007, accompanied by archaeological test excavations on the lower esplanade and in the upper shelter that proved fruitless.

Fig. 3 Tracing of the painted figures from the 2014 DStretch enhancement of a RGB photographic coverage of the painted rock wall (DAO : C. Defrasne)

B. Rock art

The Otello rock shelter is the most densely decorated shelter in southern France, with more than 300 recognized figures, various chronological phases and many superimpositions. This iconography is also characterised by a remarkable and rare polychromy. Six different colours can be identified with the naked eye: carmine/purple, vermilion, orange, yellow, white and brown. However, great care must be taken here, as the changing colour of the wall can influence perception, as can the possibility of differential conservation of matter across the wall. Some areas of the north wall of the upper shelter, which are covered with weathering crusts or have a large number of paintings, are very difficult to decipher and the figures cannot be systematically identified. Others are now too degraded to be identified. Although the vast majority of the figures are located on the northern wall of the upper shelter (283), the entire architecture of this complex site has been taken over by the graphic act. Some figures were painted on the southern wall of the upper shelter (22), which is very irregular, and some traces of paint are visible on the wall of the lower esplanade. Furthermore, some figures have been painted on the northern wall of the lower esplanade, on a rocky ridge that is now difficult to access and requires safety equipment. Similarly, the north wall of the upper shelter has been painted to the limits of its accessibility, with the last paintings being located above the void. There are also numerous stains of pictorial matter on the ceiling of the shelter. The omnipresence of these remains of pictorial matter, to which are added other anthropic indications of modifications of the site, invite us to consider that the Otello shelter was thus conceived by its users as an architectural ensemble fully occupied by social activities. The floor of the lower and upper shelters is composed of a yellow or orange powdery sediment with strong colouring power questioning an in situ use of these colouring matters.

The vast majority of the paintings (41%) consist of simple marks or figures that are difficult to characterise due to the lack of familiar referents or ordinary structure. In spite of this, we can see that most of the graphic expression in the Otello shelter is composed of cruciforms (59, 19%), reticulated, circular (17, 6%) or quadrangular (30, 10%), anthropomorphic figures (27, 9%) and scutiforms (12, 4%). In addition, there are a few punctuations and single examples of other types of figures (anchoriform, honeycomb, shovel-shaped, stelliform). It is worth noting that there are no animal figures.

Concerning the iconographical study, Ph. Hameau looked for the possible logics that structure this chromatic diversity and proposed to associate four of these colours with four successive graphic phases. In addition to this chronological evolution, he envisaged a spatial progression of these colours from the right to the left of the wall, although this did not exclude some superimpositions and overlaps. According to him, carmine red, vermilion red, orange and yellow would follow one another. He also noted for each of the phases, a thematic replication of the previous one (Hameau 2011). The observations we made partly corroborated Ph. Hameau's one but now require a systematic analysis of their spatial distribution and relative chronology to be confirmed, invalidated or clarified. Indeed, some superimpositions invite us to consider a greater complexity in the use of colouring matter. However, understanding the spatial and chronological distribution of the colouring matter was previously made very difficult because (i) of complex superimpositions within which DStretch failed to separate the individual figures; (ii) the changing colour of the wall which modifies the perception of the colour of the figures.

C. Structure of rock art and colouring matter issues: nature, provenience, chronology and taphonomy

As previously mentioned, understanding Neolithic schematic expression, its cognitive nature and its social uses, requires an analysis of its syntax. In this respect, colouring matter constitutes an irreplaceable vector of information. Their study, carried out with the help of in situ analysis methods (micro XRD, XRF, diffuse reflectance spectroscopy, hyperspectral imaging) or micro-samples studied in the laboratory (optical microscope, SEM, Raman spectroscopy, micro XRF, XRD/micro-XRD, tomography), makes it possible to question the nature of the colouring matter used and their origin, the possible anthropic mixtures used to produce the pictorial matter, the interactions with the weathering products of the wall and the geomorphological evolution of the site, as well as their relative chronology, notably through micro-stratigraphies. Due to the characteristics of the iconography (numerous figures, various chronological phases, various colouring matters, numerous superimpositions), the Otello rockshelter allows us to address all these scientific issues. It should also be added that the site contains sources of colouring matters which raise questions about the use of the matters for graphic purposes. Finally, the shelter is located in a geological context well known for its sources of colouring matter, near Les Baux de Provence, the town that gave its name to bauxite. These sources of colouring matter may have been exploited in prehistoric times. Thus, at the Otello shelter, the archaeological issues associated with the study of colouring matter are multiple. Do the different colours perceptible to the naked eye correspond to a variability in the composition of the matter? Where do they come from? Were the colouring matter present in the rock shelter used to produce certain paintings? Do the different colouring matters correspond to distinct chronological phases? How are they distributed across the wall? Can we identify groupings of figures on the basis of their composition and could they help us to understand how the schematic expression is built? The study of colouring matters mobilising the complementarity of in situ and laboratory analytical methods as well as point and surface analyses is underway as part of a PhD[1] and collective research programmes[2]. Such analyses are indeed needed to confirm and complete compositional information from hyperspectral imaging tested here for future development and more systematic use.

D. Why use hyperspectral imaging?

The use of hyperspectral imaging at Otello has two main objectives: (i) to overcome the shortcomings of one of the most widely used pairs of tools in rock art archaeology today, RGB cameras and DStretch software, and to allow a better recording of the rock art (exhaustive inventory of paintings and separation of the superimposed figures); (ii) to overcome the lack of representativeness of point analyses of colouring matter by adding a spatial dimension to the study and, (iii) to help the taphonomic analysis of the painted wall, inseparable from the study of the colouring matter.

---

[1] PhD by C. Théron (dir. P. Martinetto/Néel Institute and C. Defrasne/EDYTEM; co-supervision: E. Chalmin/ EDYTEM; 2022 - 2025) funded by the MITI (CNRS Interdisciplinary Mission)

[2] Analyses of colouring matters are also carried out in the framework the Graphein project (dir. C. Defrasne) funded by the Ministry of Culture.

If the use of DStretch software had made it possible to double the number of figures identified between the initial recording of the shelter and the recording carried out in 2014 (Hameau 2011; Defrasne et al. 2021), a certain number of figures and superimpositions remained misunderstood and indistinguishable, prohibiting a precise restitution of the relative chronology and the syntax of the iconography. As a non-invasive method for enhanced reading of painted walls, hyperspectral imaging appears to be a further step in the evolution of rock art recording techniques.

Moreover, it was necessary to complete the panel of the in situ and laboratory methods of analysis of the colouring matter. In-situ and non-invasive analyses are generally composed of point measurement techniques, such as X-ray fluorescence spectrometry (XRF), handheld Fourier transform infrared spectroscopy (FT-IR), fibre optics reflectance spectroscopy (FORS) and Raman spectroscopy. In our case, diffuse reflectance spectroscopy covering the entire visible and near infrared range (0.4- 2.5 μm) is implemented by means of a portable spectrometer with a millimetric spot measuring handle designed for this purpose. The aim here is to access the true colour of the pictorial matter and to characterise the mineral and organic materials from the radiation they reflect when they are illuminated by a light source. Each mineral has characteristic light absorption bands allowing us to characterise a diversity of materials invisible to the naked eye and to group figures together on the basis of their composition. However, point measurements are often selected from visual inspection alone, and therefore may not be representative of the whole wall. Hyperspectral imaging allows to map the spectral heterogeneities and therefore to identify the location of the most diverse spectra, which represent the purest pixels (i. e. the less mixed areas, also referred as spectral “endmembers”). The study of such data is underway as part of the research work mentioned above.

Then, the use of hyperspectral imaging and the addition of a spatial dimension to the analysis of the colouring matter, complementary to the different point analyses, will allow us to map the different pictorial matters and to gather the figures on the basis of the analysed composition, instead of its visual colour only. It is expected that this could lead to a better understanding of the structure of the iconography and eventually identify local repainting and superimposition (Bayarri et al. 2019).

Finally, the study of the colouring matter is inseparable from that of the taphonomy of the wall. Indeed, it cannot be done without an analysis of the alteration processes that affected the rock wall before, during and after the paintings were made and that modify the composition of the pictorial matter. This taphonomic approach is carried out at different scales, in interaction with the archaeo-geomorphological study of the site as part of an integrated approach. Hyperspectral imaging is expected to assist in the mapping and characterization of wall weathering facies.

Before a systematic implementation of the method, we wanted to test the potential contribution of hyperspectral imaging to the study of rock art in the context of the resumption of studies of the Otello schematic rock art site.

III. In situ implementation of hyperspectral imaging

Previous hyperspectral studies on rock art used visible-very near infrared (VNIR: 400-1000 nm) hyperspectral cameras (Bayarri et al. 2019; Jones et al. 2020). For this study we used both VNIR and SWIR (Short-Wave InfraRed: 1000-2500 nm) hyperspectral cameras (Fig. 4).

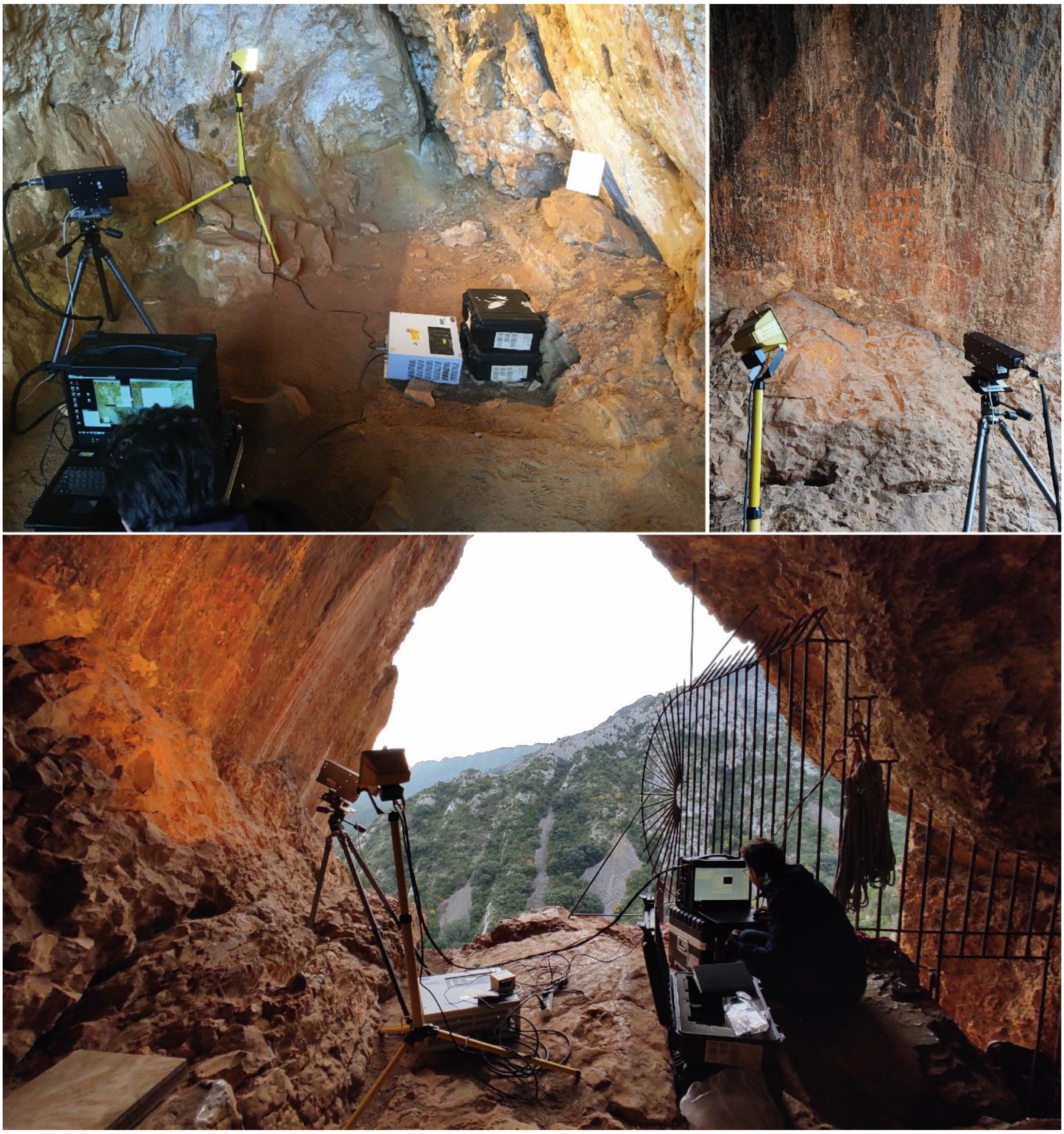


Fig. 4 VNIR (Visible and Near-InfraRed: 400-1000 nm) and SWIR (Short-Wave InfraRed: 1000-2500 nm) hyperspectral cameras in the Otello rockshelter (november 2021) (photo : C. Defrasne)

Indeed, SWIR is generally a very discriminative spectral range for mineralogical identification. As the pigments used in rock art are mainly minerals, as well as the weathering crusts, we can guess that the coupled use of visible and infrared hyperspectral cameras could provide new information. In the context of these tests on the application of hyperspectral imaging to rock art archaeology, we also wanted to question the respective contributions of the VNIR and SWIR acquisitions of the same scene in the same lighting conditions and their complementarity for the detection of new figures. However, infrared cameras are much less portable than visible cameras and need specific lighting. Their use in a rock shelter is thus more challenging.

A. Instruments

The hyperspectral cameras used in this study are manufactured by the Norwegian company NEO (Nork Elektro Optikk). They are push-broom sensors: they acquire one vertical line of pixels at a given time, with a spectrum for each pixel of the line. The second dimension of the image is obtained using a scan, with a rotation around the vertical axis of the camera. We used two different sensors:

- the VNIR sensor (HySpex VNIR-1600) has a spectral range from 400 nm up to 990 nm, a spectral sampling of 3.7 nm (160 bands) and a spatial definition of 1600 pixels on a 17° field of view, corresponding to 0.56 mm per pixel at a distance of 3 m.

- The SWIR sensor (HySpex SWIRe-320) has a spectral range from 900 nm up to 2500 nm, a spectral sampling of 6 nm (256 bands) and a spatial definition of 320 pixels on a 14° field of view, corresponding to 2.3 mm per pixel at a distance of 3 m.

Outdoor measurements ideally require a clean blue sky with no clouds, so that there is no fluctuation in illumination. As the Otello rock shelter is open, but relatively deep and narrow (about 12 x 3m), sunlight enters the shelter but did not directly illuminate most of the wall. The diffuse light reaching the walls is scattered by the sky and reflected by the surrounding landscape, but its intensity is insufficient for our acquisition, in particular in the near-infrared which is poorly scattered by the blue sky. Moving clouds can also induce important fluctuations in the light thus disrupt the spectral measurements. We thus need a clear or homogeneous sky and an additional artificial source of light. We selected a 300 W halogen spotlight, because it emits a continuous spectrum of energy over the whole 400-2500 nm spectral range.

The joint operation of the hyperspectral cameras, the computer and the spotlight in the Otello shelter, requires electricity, provided by a small 2 kW power generator. All the equipment weighs 112 kg.

B. **Set-up**:

In order to have homogeneous measurements with the same spatial resolution and illumination-observation conditions we need to place the cameras at the same distance from the wall all along the painted wall.

Because of the shelter topography, the cameras were placed at 3 metres from the wall. This configuration leads to VNIR and SWIR images of 90 cm and 74 cm height respectively, corresponding to images pixel sizes of 0.56 mm and 2.3 mm respectively. In order to limit image deformation, illumination changes and variation in the observation angle we need to restrict the width of the acquired images along the scan direction to 200 cm. This implies the acquisition of about 15 images for each sensor in order to cover the entire north wall. To optimise the detector signal, we used a long integration time of 100ms for VNIR (ie. the camera slit was opened 100ms for each line) and 18ms for SWIR. To further improve the signal-to-noise ratio we also used a software averaging 5 acquisitions of each line on both VNIR and SWIR. This resulted in a 45 minutes acquisition for each VNIR hyperspectral image and 5 minutes for SWIR. The size of the recorded images is typically 1600 x 3000-4000 pixels for VNIR and 320 x 1000-1200 pixels for SWIR.

To calibrate the data in reflectance and to apply atmospheric correction, we placed a large white reference panel (99% Spectralon™) of 25x25 cm inside each observed area (near to its border) but away from the painted area.

C. Data processing

Before doing any in-depth analysis of an image, the data has to be converted into reflectance (i.e. a normalised percentage of the incident radiant flux). First, right after acquisition, the raw sensor digital counts of the data cube are converted into radiance energy. This step is done in the NEO software as it involves the factory calibration of the instrument. We then proceed to convert this radiance into reflectance. For each wavelength, we calculate a mean radiance value on some pixels selected in the Spectralon™ area. Then all the radiance spectra of the image are divided by this mean reference radiance spectrum, and the resulting reflectance spectra are stored in a data cube (Fig. 5).

Fig. 5 Flowchart of data processing (M. Giraud).

Different mathematical transformations are generally used in space exploration and Earth's remote sensing to analyse hyperspectral image cubes. Their aim is to reduce the dimensionality of the useful data and to separate the signal from the noise. In this study we used the Independent Components Analysis (ICA) (Hyvärinen and Oja 2000). It is expected to be one of the most efficient algorithm to separate different types of paintings as well as the wall taphonomy because its assumptions of independence and non-gaussian statistics of its components are more relevant for natural and human-made scenes than PCA (gaussian statistics, linear combination of components). In image processing, PCA can be used to reduce the dimensionality of an image while preserving the most important features, while ICA can be used to separate an image into its independent sources and detect weak features. In space exploration of planetary surface PCA is frequently used for denoising application and mapping of the major surface components (see e.g; Schmitt, et al., 2017). Schmitt et al. (2022, in review) recently compared DStretch, PCA, ICA and MNF algorithms in the case of rock art painting and found that ICA was clearly the most efficient algorithm for revealing faint or very localised figures in the images and separating them and from the rock wall.

In addition, a first test of extraction of the pixels containing pigment and their classification has been performed. We run it on the VNIR-016 image. Using ENVI™ hyperspectral toolbox software we first selected the nine ICA layers containing information on pigments and rock wall and then we selected 1 or 2 ROI (Region Of Interest) of end-member pixels (about 75 pixels each) for each of the six ICA layers displaying information on painted figures. A total of 10 ROI has been used in a SAM (Spectral Angle Mapper) classification run on the 9 selected ICA layers (threshold angle: 0.6 rad). This resulted in 10 classes of pixels which were finally merged in 7 distinct classes owing to some spectral similarity of 3 couples of classes. We finally applied a series of spatial sieving and clumping iterations to all classes in order to partly reduce the number of isolated, or small groups of pixels and to partly fill the small holes inside the classes, mostly due to measurement noise and to the high spatial variability of the illumination and reflectance of the fine rock texture.

IV. Results

In this part we analyse a few of the test hyperspectral images recorded on the north wall of the Otello shelter (Figure 6) and highlight the new information we can get on the pigment composition and the wall taphonomy as well as on the painted figures and their spatial distribution. We also discuss the relative contribution of the VNIR and SWIR spectral ranges to this new information.

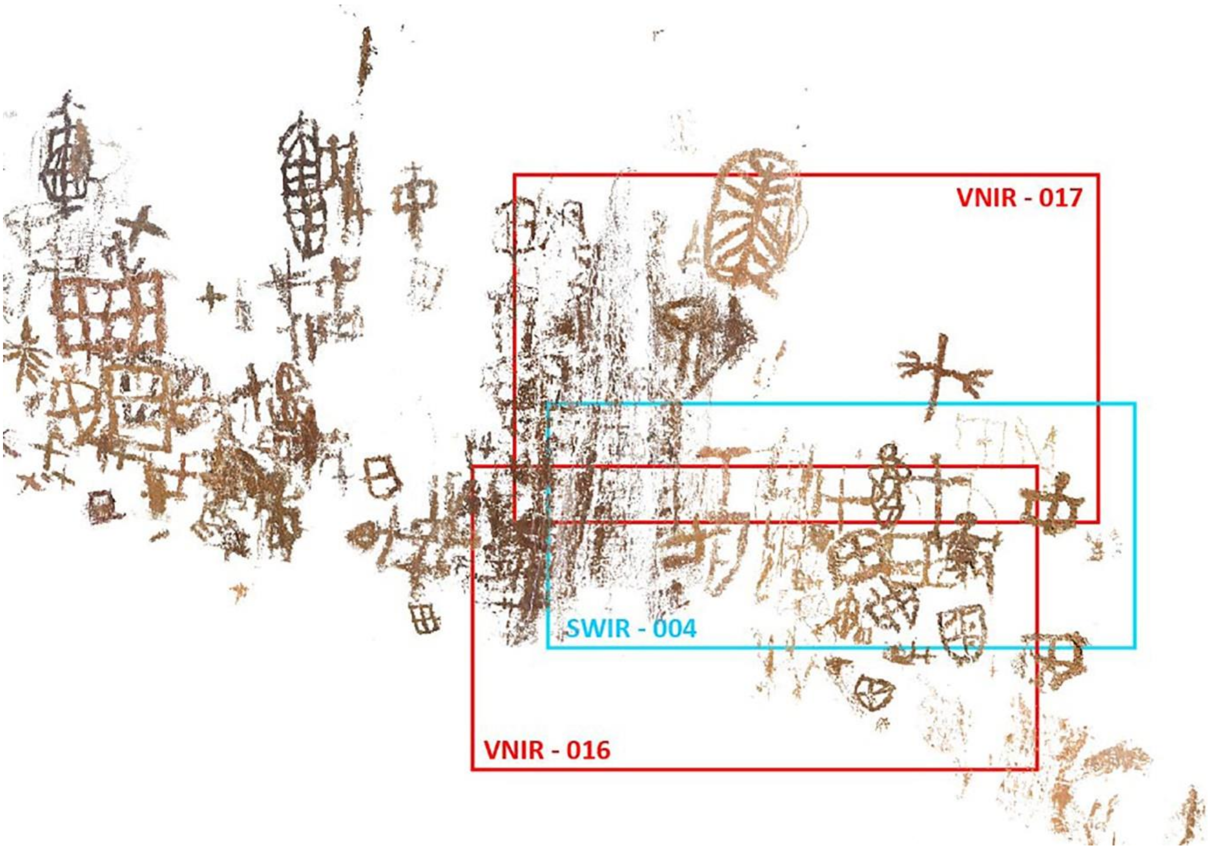
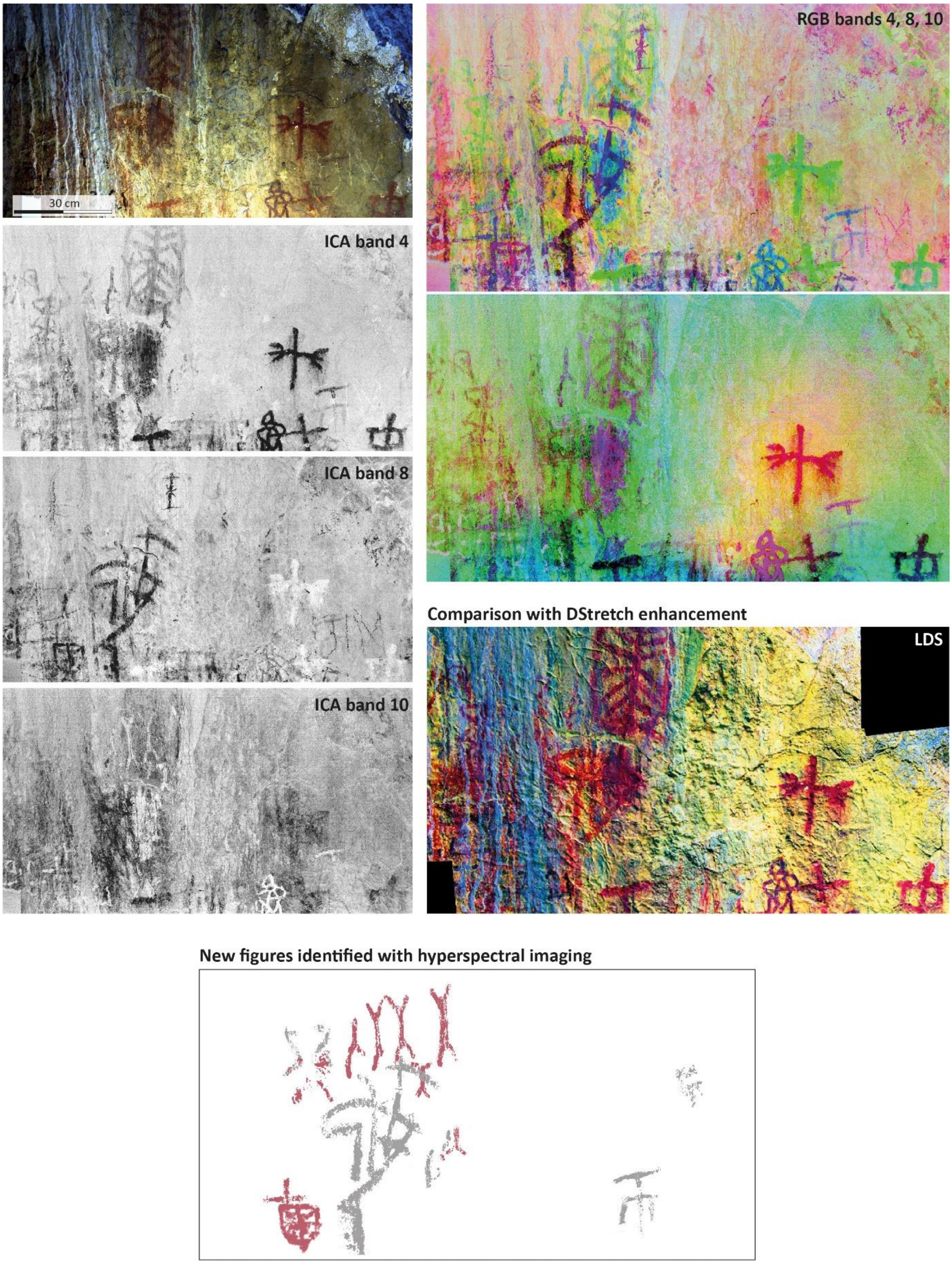


Fig. 6 Position on the tracing of the north wall of the Otello shelter of the different VNIR and SWIR hyperspectral images studied

A. Identification of new painted figures

The first notable contribution of VNIR and SWIR hyperspectral imaging consists, in addition to an improvement in the readability of the paintings, in the highlighting of painted figures invisible to the naked eye or in RGB camera images despite systematic image processing such as with the DStretch plug-in of the Image J software. This applies to figures that have been almost completely erased, to figures that are superimposed or completely covered by concretions.



Comparison with DStretch enhancement

New figures identified with hyperspectral imaging

Fig. 7 Illustration of the contribution of VNIR hyperspectral imaging in reading painted rock walls and comparison with image enhancement with DStretch. Image VNIR-017: Top left: synthetic RGB image using the hyperspectral data at 605 µm (R), 554 µm (G), 449 µm (B), with below three of the extracted ICA components (#4, 8, 10) containing painting information. Top right: RGB synthetic image built with these three components (R: #4, G: #8, B: #10). Middle right: Same but with R: #6, G: #4, B: #10. Bottom right: LDS DStretch enhancement of a picture taken in 2014 for comparison. The drawing at the bottom highlights the new figures identified (pink) or clarified (grey) thanks to VNIR hyperspectral imaging, including a group of anthropomorphs of a type previously unknown in Mediterranean France, as well as a new crest-shape figure, a cross and a probable human figure with outstretched arms typical of the Otello rock shelter (Analysis : M. Masse ; CAD : C. Defrasne)

In the case of the Otello shelter, this not only makes it possible to enrich the graphic corpus with numerous new figures, but also with new themes hitherto undocumented in this shelter, and relatively rare on the scale of Mediterranean France. Figure 7 illustrates such a contribution of hyperspectral imaging with the VNIR-017 image. Its statistical analysis using ICA transformation allowed us to extract several components most probably related to the distribution of different pigments (different materials or texture). The three mains are presented in figure 7, left and combined to provide synthetic RGB pictures of the paintings.

Many new figures are clearly identified or clarified in these ICA components, including a group of faint anthropomorphs of a type previously unknown in Mediterranean France. We can now question their relative chronology and their existence on other sites. In the same way, solar and star shape figures have been evidenced in an infrared processed hyperspectral image (SWIR-004, Figure 8) (see Fig. 6). Solar shape figures are rare in southern France and the first ones identified in the Otello rockshelter.

Understanding the syntax of the graphic expression requires placing the figures in the temporal succession of the graphic acts that make up the graphic ensemble we are studying today. However, a large number of superimpositions remained indistinguishable and the figures composing them inseparable despite the use of DStretch (Figures 7 and 8). Hyperspectral imaging greatly alleviates this problem. By helping to read the superimpositions, hyperspectral imaging also makes it possible to question the relationships between the different and successive graphic phases. Indeed, the centre of two of the figures identified in Figure 8, a star figure and a cross, coincides perfectly. As for the particular appearance of one of the anthropomorphic figures, it is now explained by the adaptation of the body of the figure to the contours of an earlier grid (Figure 9). These new images also complete the chronological sequences of the painting phases, the global vision of which now requires systematic acquisitions on the scale of the shelter.

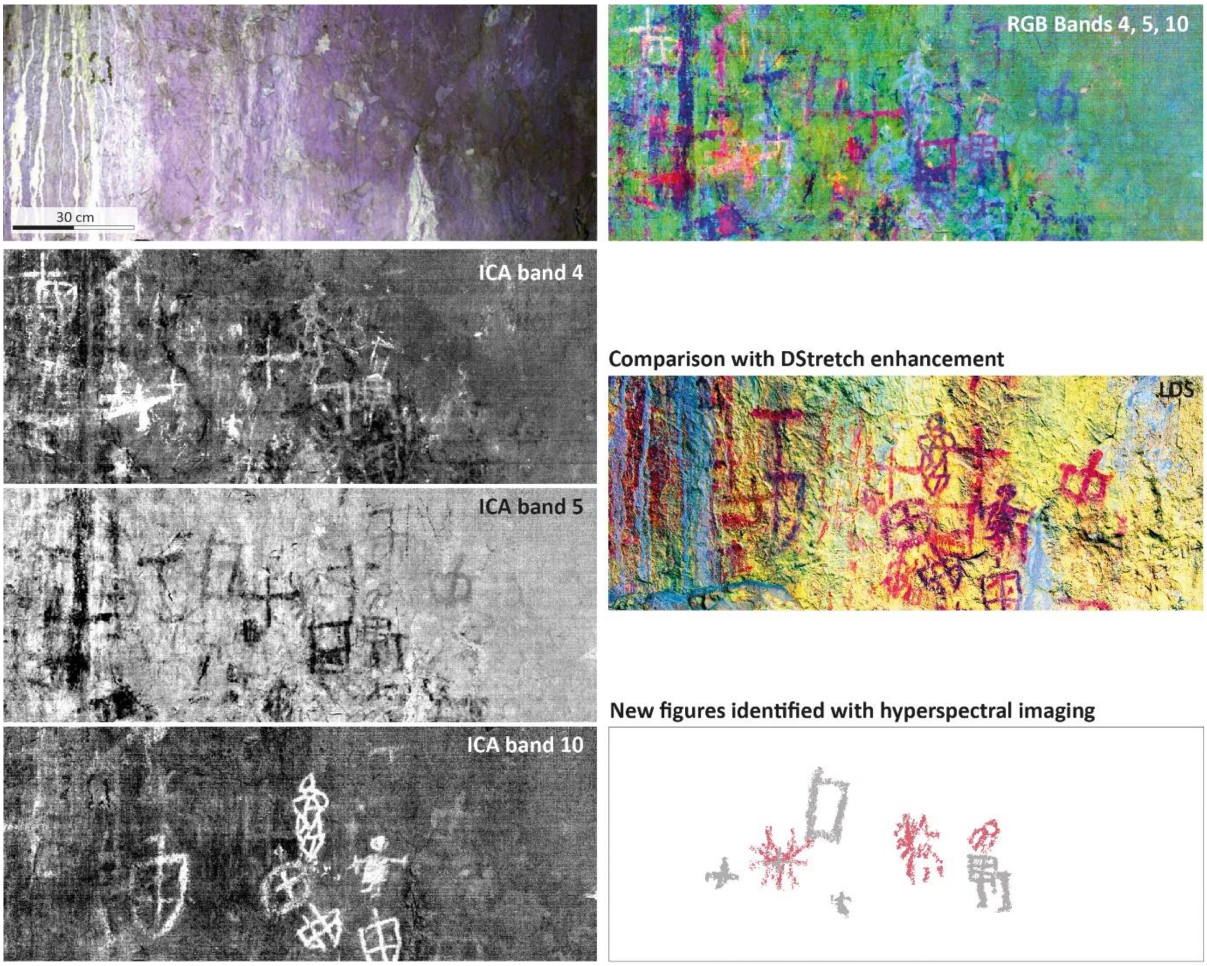


Fig. 8 Illustration of the contribution of SWIR hyperspectral imaging in reading painted rock walls and comparison with image enhancement with DStretch. Image SWIR-004: Top left: synthetic RGB image using the hyperspectral data at 1448 µm (R), 2169 µm (G), 1255 µm (B), with below three of the extracted ICA components (#4, 5, 10) containing painting information. Top right: RGB synthetic image built with these three components (R: #4, G: #5, B: #10). Middle right: LDS DStretch enhancement of a picture taken in 2014 for comparison. Bottom right: drawing highlighting the new figures identified (pink) or clarified (grey) thanks to SWIR hyperspectral imaging, including star and solar shape figures, grids and crosses (Analysis: M. Masse; CAD: C. Defrasne)

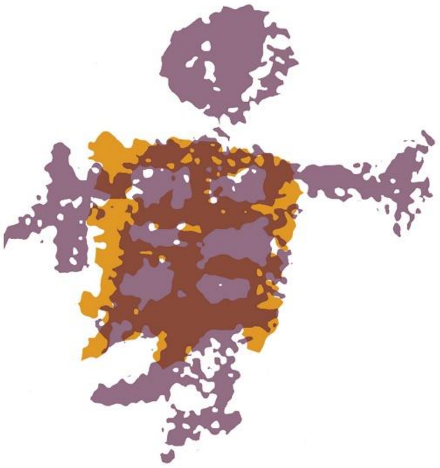
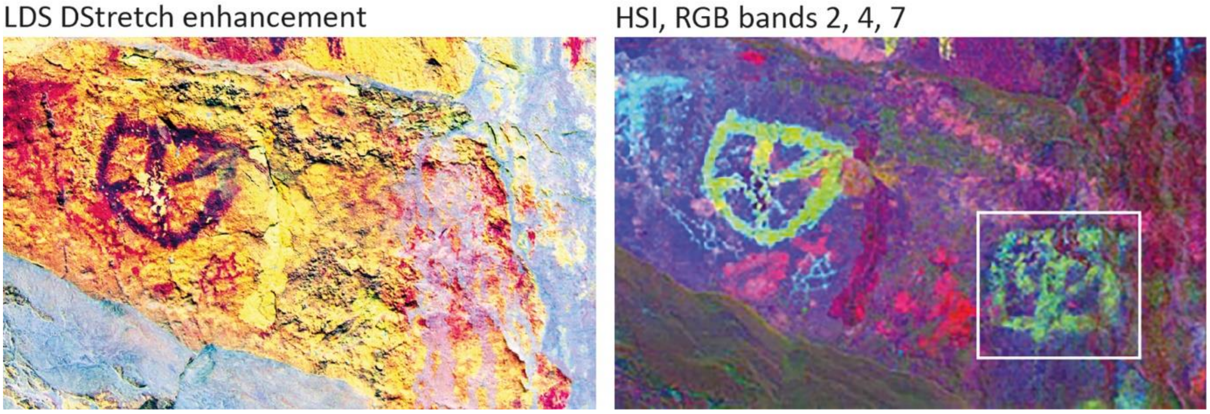


Fig. 9 superimposition of two Figures evidenced by infrared hyperspectral imaging (image SWIR-004, Fig. 8) and explaining the particular shape of the human figure (CAD: C. Defrasne)

We also noted that hyperspectral imaging makes it possible, when the crusts are not too thick, to identify figures that have been covered up and that are totally invisible to the naked eye.

A good example can be seen in the hyperspectral image VNIR-016 where a grid or crest shape figure, covered by calcite crusts, and not distinguishable with DStretch enhancements, can now be easily recognized and recorded (Fig. 10).



LDS DStretch enhancement

HSI, RGB bands 2, 4, 7

Fig. 10 A grid or crest shape figure covered by weathering crusts and not distinguishable with DStretch enhancements, is evidenced by hyperspectral imaging. Left: LDS DStretch enhancement of a picture taken in 2014 for comparison. Right: part of the RGB synthetic image built with three ICA components of image VNIR-016 (R: #2, G: #4, B: #7) containing painting information (Analysis: M. Masse; CAD: C. Defrasne)

These first results demonstrate that hyperspectral data acquisition in both the visible and infrared spectral ranges can provide new information compared to standard RGB cameras. It should also be noted that the results obtained with each of the cameras seem complementary. Figure 11 illustrates, for example, the contribution of SWIR hyperspectral cameras compared to VNIR ones. The solar and star shape figures, completely invisible to the naked eye, are only visible on SWIR acquisitions.

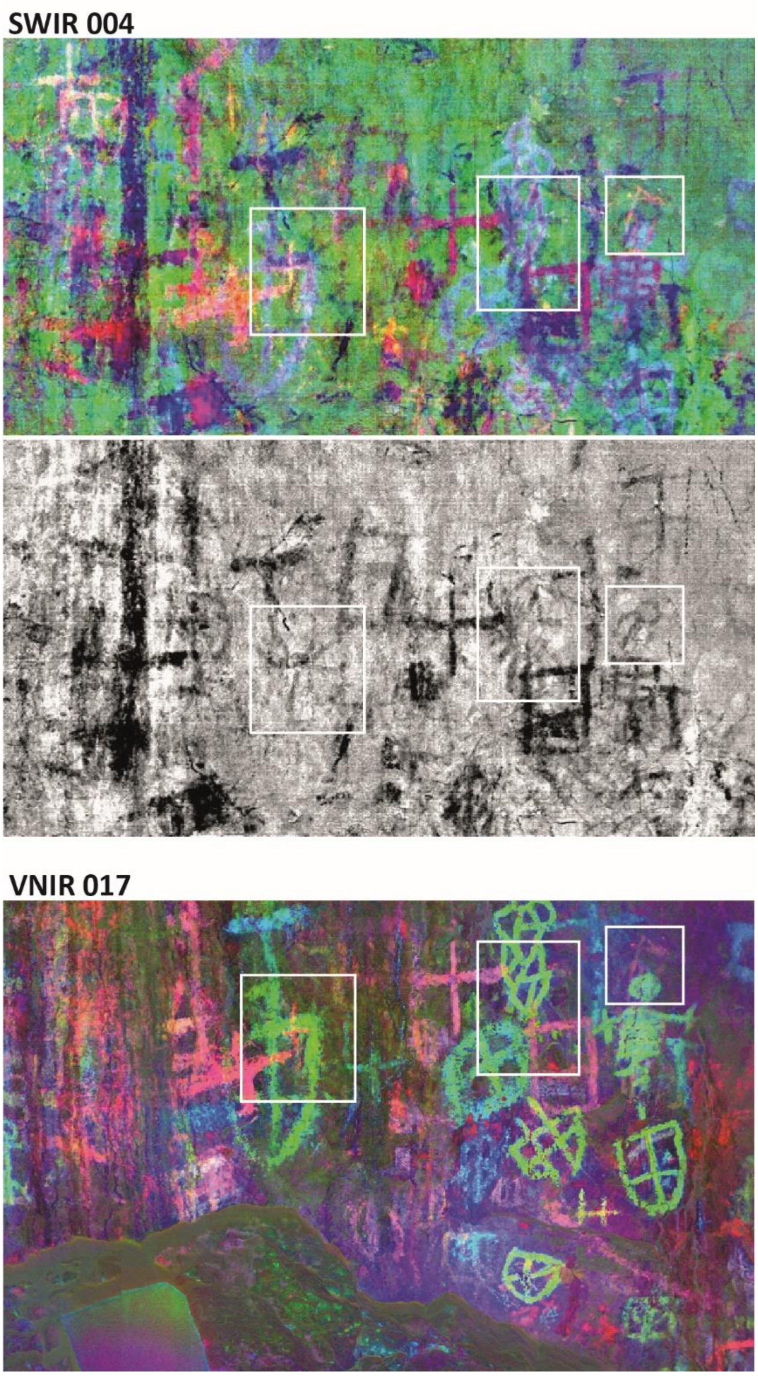


Fig. 11 Illustration of the complementarity of VNIR and SWIR acquisitions. The solar and star shape figures only appear on the SWIR acquisition. The white boxes give the location on both VNIR and SWIR images of the figures only seen with the SWIR image. The central image is the ICA component which displays them

In the same part of the painted wall, data obtained with VNIR and SWIR hyperspectral cameras reveal different and complementary new paintings. This difference can be explained by differences in the pigment composition. The penetration depth of the light being essentially inversely proportional to the square root of the absorption coefficient (Clark and Roush 1984), it is generally larger at wavelengths with higher reflectance in the spectrum, i.e. outside absorption bands. Most of the red or orange-yellow chromophore pigments containing iron-bearing minerals (hematite, goethite, …) very strongly absorb in at least part of the visible range but become more reflective in the near-infrared above about 900 nm, outside their absorption bands (see e.g. (Chalmin et al. 2021), Fig. 7). In the SWIR range, the penetration depth of the radiation is thus stronger and the hyperspectral data probes deeper layers. They should therefore be more relevant to distinguish superimposed paintings.

By evidencing these new images, hyperspectral imaging makes it possible (i) to approach the exhaustiveness of the rock art recording and thus complete our knowledge of the graphic repertoire used by prehistoric societies; (ii) to complete areas of the rock wall that we thought were empty; (iii) to help study the superimposition of the pigments (complemented with other techniques) and thus the relative chronology of the graphic acts; (iv) to document the graphic practice by highlighting repaints or the mobilisation of a previous shape in the structure of a new figure; and finally (v) to allow a better knowledge of the spatial distribution of the figures at the scale of the wall, and of their organisation. It is only on this basis that the syntax of schematic rock art can be informed and its cognitive nature questioned.

B. Taphonomy of the wall : distinguish the weathering crusts

The multi-analytical characterisation of the colouring matter (in situ and microsamples) and its superimposition is essential for understanding the syntax and relative chronology of the graphic compositions. However, this requires a detailed understanding of the close environment of the figures, in other words of the taphonomy of the rock wall, in order to isolate the signal of the different colouring matter from the weathering processes of the rock surface.

In addition to helping recognize the painted figures, an in-depth analysis of hyperspectral images allows the mapping of wall texture and their mineralogy (and possibly also biology). In this way, weathering crusts similar to the naked eye can be distinguished, highlighting different alteration processes and their relative chronology. All this information should allow a better interpretation of the history of the rock wall and of the composition of the paints determined with the hyperspectral data, but also of the micro-samples collected on the wall and analysed in the laboratory, considering the global wall context.

The identification of the composition of the weathering crusts is efficient with infrared data (Figure 12) which contains numerous characteristic absorption bands of minerals (see e.g. Chalmin et al. 2021, Fig. 7), but much more difficult with visible data which are mostly sensitive to the iron-bearing chromophore minerals, the other minerals (e.g. calcite, gypsum, kaolinite, quartz, …) being essentially ‘white’ in this range. This could allow us to map the mineral composition and texture of the crust using their specific spectral signature (Fig. 13). The large penetration depth (up to a few mm) of the radiation inside these infrared transparent materials (outside the main absorption bands) may further allow us to probe the wall composition under thick crusts.

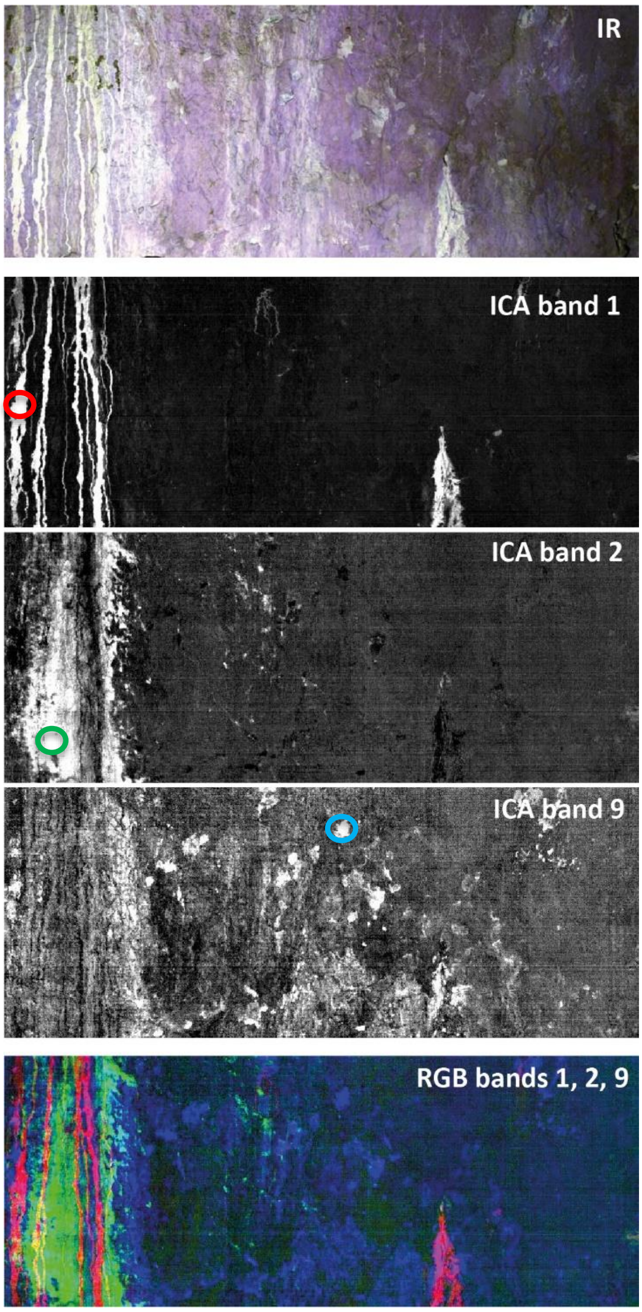


Fig. 12 Distinction of various crusts, with different composition, interacting with the paintings and indistinguishable to the naked eye. Part of image SWIR-004: three of the extracted ICA components (#1, 2, 9) containing rock wall and crust information. The coloured circles depict the area where the end-member spectra of each component, displayed in Figure 13, have been extracted. Bottom: RGB synthetic image built with these three components (R: #1, G: #2, B: #9)

For the North Otello wall we extracted an average spectrum corresponding to the end-members (group of pixels among those having the highest values) of three ICA components (#1, 2, 9) depicting the wall crusts in image SWIR-004 (Fig. 12) and we compared them with laboratory near-infrared reflectance spectra of relevant minerals measured at IPAG (Institute of Planetology and Astrophysics of Grenoble) and available in the GhoSST@SSHADE database (Schmitt et al. 2018). This allows us to identify the high values of ICA component #1 as depicting the presence of fine-grained calcite (with some water), component #2 as gypsum (with some calcite and Fe-oxides), and component #9 as a mixture of calcite and gypsum (Fig. 13). However, a detailed analysis of the composition and texture of this rock wall should be very complex, with up to 8 ICA components representing their various types of variation, and is out of scope of this first paper dedicated to the analysis of the rock art figures.

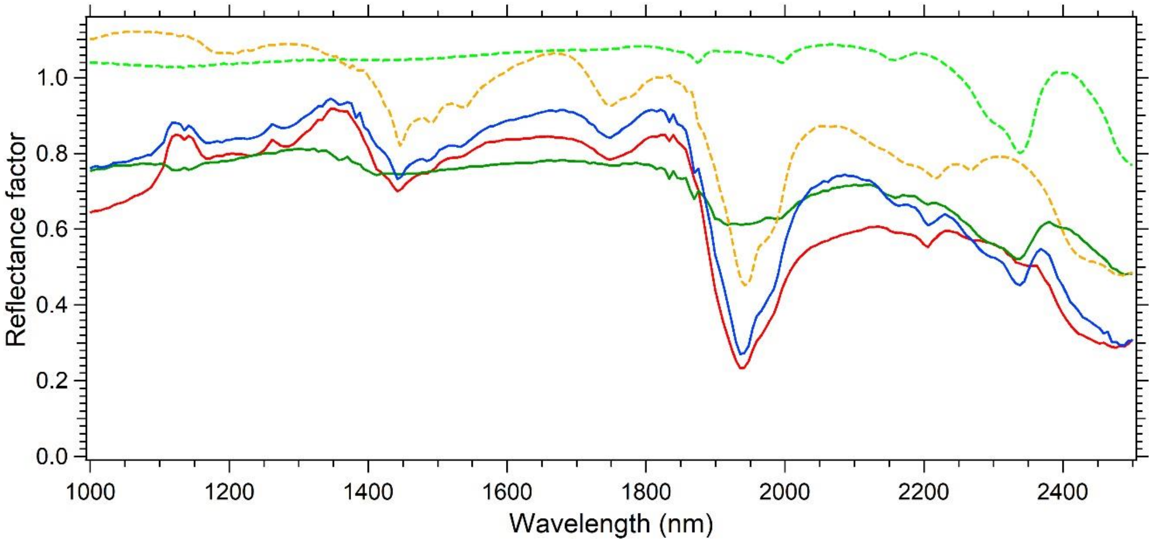


Fig. 13 Preliminary identification of the weathering crusts. Comparison of the SWIR end-member spectra of three ICA components (located with a coloured circle in Fig. 12) depicting the wall crusts in image SWIR-004 (Fig. 11) with laboratory near-infrared reflectance spectra (GhoSST@SSHADE database, Schmitt et al. 2018). Component #1: calcite with a little gypsum (dark green), #2: gypsum with some calcite and Fe-oxide (red), #9: mix of calcite and gypsum (blue). Lab spectra of pure minerals: Calcite fine powder (light green, dotted), Gypsum (orange, dotted).

C. Pigment classification

The classification process using the classical Spectral Angle Mapper (SAM) tool, but applied on a set of selected ICA components (the first 9) from the VNIR hyperspectral image VNIR-016, allows to distinguish 6 or 7 different classes of pigments (Figure 15) which have good spatial coherence and mostly appear to be homogeneous with no or little mixing with another class on a particular figure. Each pigment class is also common to several figures, pointing to the possibility that they have been painted with the same pigment, or batch of pigment, and/or technique.

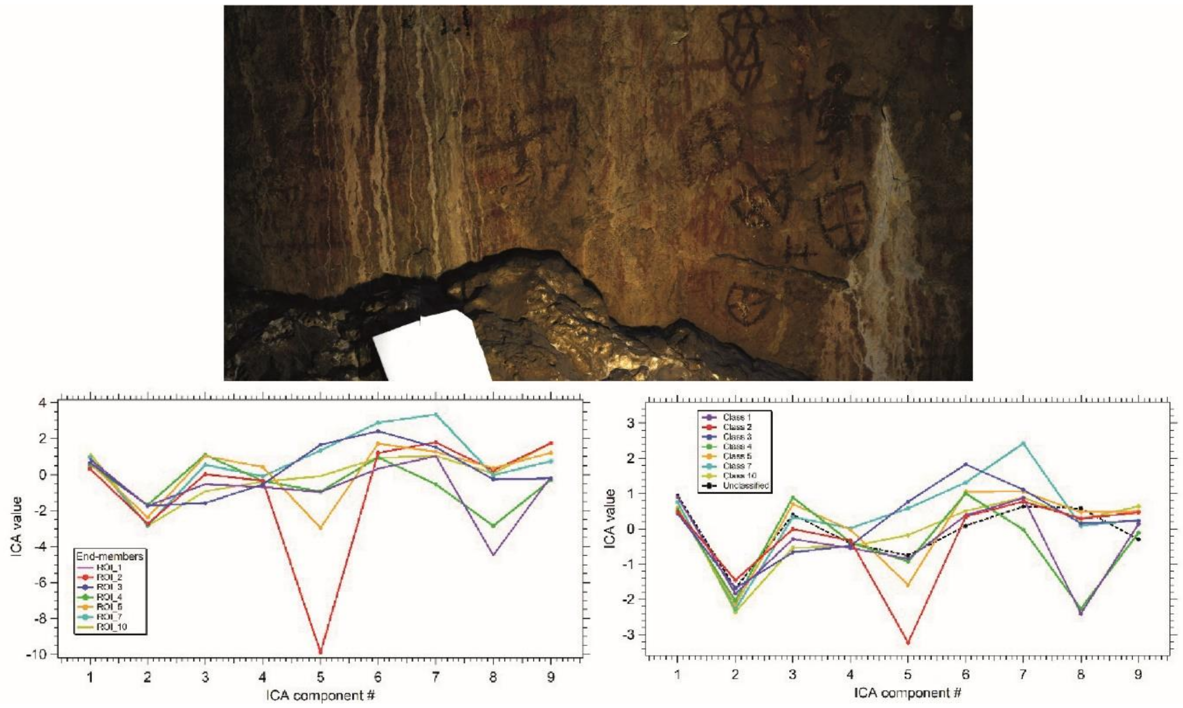


Fig. 14 Endmember and average ICA spectra of the 7 classes of pigments obtained for the image VNIR-016. The colour of the curves corresponds to the colours of the pigment classes on figure 12, and the black dotted line to the average ICA spectrum of the rock wall. Strong variations between the different classes of pigments are observed in ICA #5, 7 and 8 and moderate in ICA 3, 6 and 9: they allow to more easily discriminate between the different pigment classes. The rock wall is mainly depicted with ICA #1, 2 and 4.

The comparison of the endmember and average ICA ‘spectra’ of each class (Figure 14) allows to see their specific ‘ICA signature’. The strong variations between the different classes of pigments observed in ICA components #5, 7 and 8 show that they are the most discriminating between pigments, while components #3, 6 and 9 add more subtle differences. On the other hand, components #1, 2 and 4, mostly depicting the rock wall texture, are not discriminating for pigments. Detailed analysis of the statistical distribution of values for each of the seven classes shows that any pair of these classes differ on at least one ICA component by more than the sum of their standard deviation. However, this set of classes and their resulting spatial distribution in the image (Figure 15) is not completely unique and partly depends on the choices made for both the ICA component and end-member selections as well a as for the optimal SAM classification angle and the final combinations of some ‘similar’ classes. In order to evaluate the impact of these subjective choices (sometimes quite well constrained) we went through the whole process a second time, on the same image, but by slightly varying these parameters (now run on only the 7 ‘pigment ICA components’ instead of the 9 ‘pigment and wall’ components; different subset of end-member pixels, slightly different final class combination). The result (not shown) is very similar in terms of classes, which is reassuring, except mostly one major change: the vertical curved line mostly included in the green class #4 (but also partly violet) in the middle of Figure 15 is now completely in the violet class #1, and thus regroups with the remaining of this figure. Also, a new dark yellow class (#10) appears on the right part of the figure, which was formerly partly in the dark blue (#3) and partly in the light blue (#7) classes. In Figure 14 we can see that the shape of the ICA spectrum of this class is similar to the light blue class, but with lower values. When looking at the normalized spectra (Figure 18 bottom) we can see that class #10 has a significantly lower slope above 600nm, possibly justifying its separate classification.

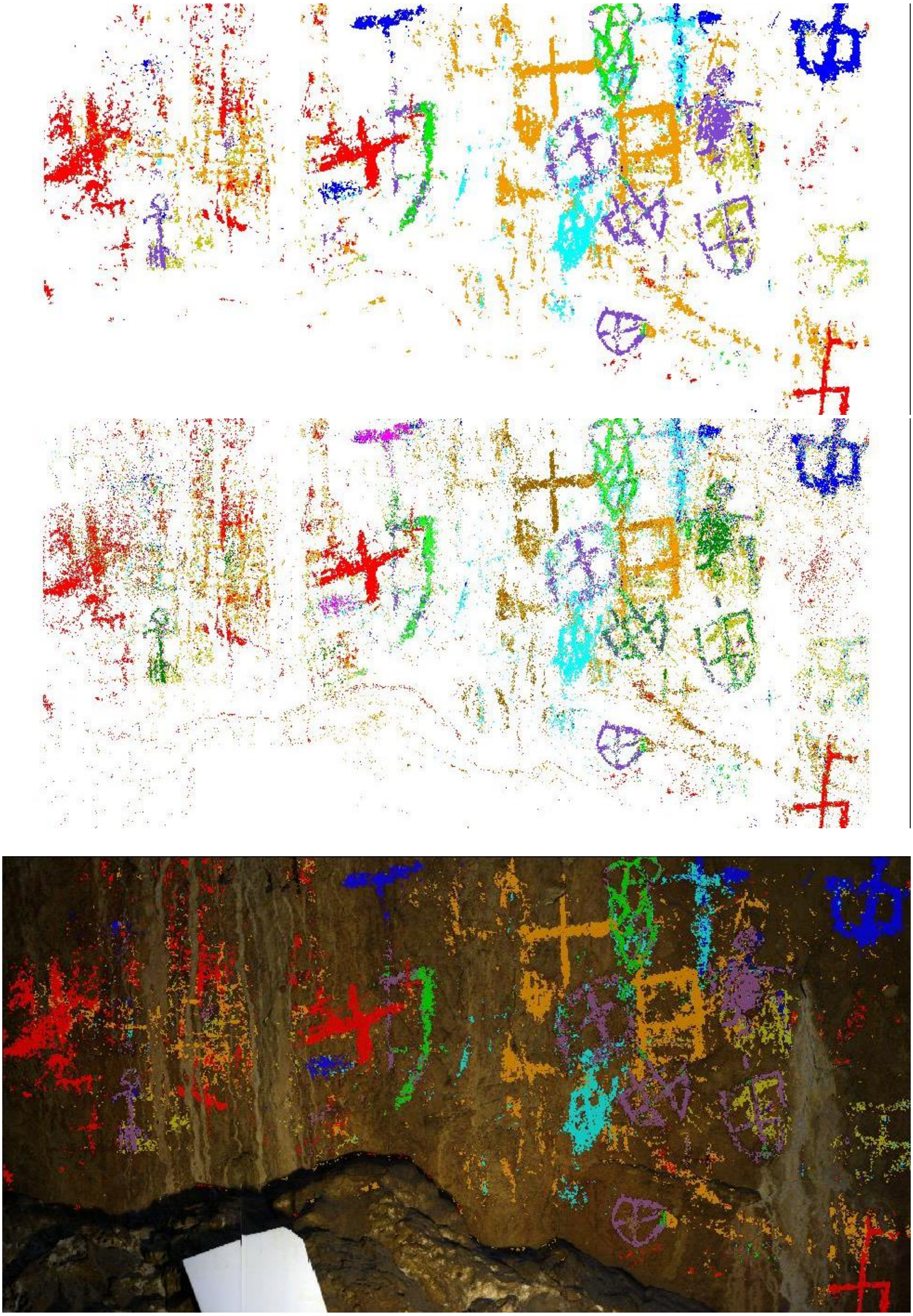


Fig.15 Pigment classification from the VNIR data. Top: the initial 10 classes of pigments obtained for image VNIR-016 using a SAM classification on a selection of ICA components containing painting information. Middle:

7 final classes obtained after merging some similar or complementary classes and applying some spatial sieving and clumping of the pixels of each class to reduce noise. Bottom: same but superimposed on a RGB image of the wall

We also attempted a classification on about the same area of the near-infrared image SWIR-004, in particular the new figures revealed in this spectral range. Unfortunately, the contrast of the ICA values (see Fig 8 and 11) and the remaining level of noise in this data set did not allowed to get a clear global classification. However, a partial classification (Fig. 16) allows to classify the 'window' superimposed below the human figure (figure 9) in the same VNIR class than the rectangle on its left (orange class #5). They have similar 'ICA spectrum'. This is consistent with the few orange pixels seen around the human figure in Fig. 15, which also suggested this classification. It also allows to suggest that the 2 new 'stars' (Fig. 8) belong to the light blue class #7. But clearly, SWIR data with better signal-to-noise ratio are requisite to fully analyse them.

Fig.16 Partial pigment classification from the SWIR data. 4 classes of pigments obtained for part of the image SWIR-004 using a SAM classification on a selection of 5 ICA components containing painting information. some spatial sieving of the pixels of each class was applied to reduce background noise. The fuchsia window on the right, where an end-member was selected, appears to be in the same class than the rectangle on its left (VNIR orange class #5).

The first interest of such a classification is that it allows to easily separate digitally the painted figures using only global mathematical operations over the whole image, not local 'photoshopping'. For example, in figure 15 (bottom) each pigment class has been extracted and individually superimposed over a RGB image of the rock wall. It even seems that this classification highlights certain otherwise illegible figures. This is the case, for example, towards the middle of the left-hand side of figure 15, where an anthropomorphic figure is clearly visible in violet (with a little blue on top). However, it should be noted that some figures with very faint pigments are currently not well included in one of the above classes as they are very difficult to separate with the thresholds currently used without adding much more 'noise' pixels from the wall rock. Higher signal-to-noise measurements and possibly the definition of other classes may be necessary to include them in the global classification.

The pigment classification also makes it possible to separate pictorial matter that are very similar to the naked eye. Indeed, we note that the green "honeycombed" figure in the top right corner of Fig. 15 is clearly distinguished from the violet figures which, to the naked eye, seemed painted with the same colour (fig. 17).

This pigment classification groups figures on the basis of spectral criteria, which can be linked to the composition of the pictorial matter. Hypotheses can then be formulated on the causes of these groupings. The first hypothesis that comes to mind is that the figures grouped in this way were produced from the same pictorial preparation. However, such a hypothesis needs to be corroborated by other studies using complementary in situ or laboratory analysis methods which are currently underway. As for the synchronous character of the figures gathered, it can be advanced without being affirmed. We also evidenced that some of the classes are closely related, and the limits between them can move depending on the classification parameters used. These continuous series of classes could more likely represent successive states of a progressive process on the same pigment, as for example the fading of paint. In any case, the formation of these groups of figures is of incomparable help in understanding the syntax of schematic rock art.

Then, the spatial distribution of these classes of pigments may tell about their temporal application as some classes appear to be superimposed over other ones. In particular near the top right of figure 15, two or three classes of pigment seem to be superimposed, the violet one appearing on top of the others. The relative chronology of the graphic acts can thus be specified as well as the chronological succession of the different "recipes" and/or colouring matter supply areas. Once again, the pigment classification reveals iconographic structures that are otherwise invisible and yet essential to the anthropological interpretation of these archaeological remains.

Then we note that certain figures seem to show several levels of superimposition. Some of them even raise the hypothesis of possible repainting since the same figures are superimposed in different colours. This constitutes information of primary importance in understanding graphic practice and, more specifically, the production of this schematic graphic expression.

Finally, the pigment classification also sheds light on the taphonomy of the wall. Indeed, in the mineral crust on the left of Figure 15 some pigments (orange class) seem to have flown over other classes (blue, and red) now only present on the side of the flow, possibly indicating that this paint has been mobilised by the mineral flow.

Fig.17 RGB picture of figures with a purple tint that seemed to be painted with the same pictorial matter (photo: C. Defrasne)

When calculating the average spectrum of each class (Figure 18) we can see that the differences between the VNIR spectra of the different pigments and those of the rock wall (global average on all unclassified pixels) are relatively small, with only subtle changes in shape and slopes in some parts of the spectra. Two of the most marked differences are the slopes above 700 nm and above 900 nm, well outside the sensitivity range of the eye (~410-680nm) and of most RGB camera detectors. The spectra are more similar below 700 nm, even compared to the rock wall which is at some places just slightly brighter (5-10%). When normalised to 1 at the shoulder at 590nm (Figure 18 bottom) we can see that the main difference below 700 nm is an increase of curvature of the spectrum in the 500-600nm range and an increased slope in the 600-700nm range which overall give slightly darker (by 5-20%) and redder colours for the pigments compared to the already mostly dark red rock wall. This explains why a RGB image processed with DStretch cannot discriminate the colour of some of the pigments from the rock wall. These visible spectral evolutions together with the deepening of the broad near-infrared absorption band around 900 nm are typical of an increasing amount of hematite from the wall to the ‘violet class’ of pigment.

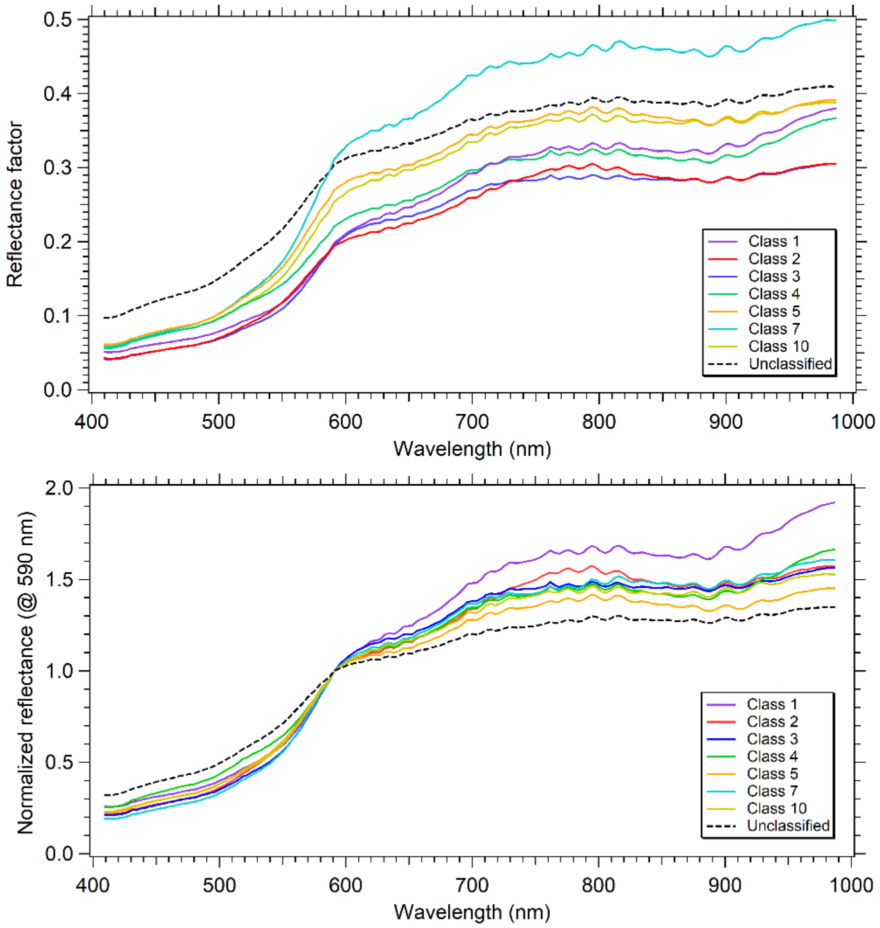


Fig. 18 Average spectra of the 7 classes of pigments obtained for the image VNIR-016 and of the rock wall. Top: reflectance spectra. Bottom: same normalised to 1 @ 590 nm. The colour of the curves corresponds to the colours of the pigment classes on figure 12, and the black dotted line to the average spectrum of the rock wall. Only subtle changes in spectrum shape and slope are observed between the different classes of pigments, characteristics of differences in amount of hematite in the pigments.

D. Some limits or improvements to be considered

The hyperspectral imaging tests carried out in situ at the Otello shelter already allow us to consider the undeniable contribution of the method to the understanding of the decorated walls, and its necessary integration, from now on, into the corpus of recording and analysis tools for rock art archaeology.

The use of only a single halogen spotlight induces a gradient of illumination all along the observed area as well as some shadowing at different scales. This may have an important effect on our ability to group the different figures as two figures with the same composition can display two different illuminations, a bias which may not be completely removed by the ICA analysis.

Fluctuations in the contribution of the outside indirect illumination of the shelter walls will also change the intensity and spectral distribution of the illumination during the horizontal scan of the image, which may take tens of minutes, thus adding an intensity and spectral pattern in the image which further deteriorates the illumination homogeneity of the scene. During some of our acquisitions we also got some fog which entered inside the shelter. Some spectral bands are sensitive to the presence of water and acquisition during this kind of weather is unreliable. A good outside weather is therefore primordial for our study.

The addition of a second light source with a different position and illumination angle, during a second field session, will improved the homogeneity and stability of the illumination, in particular by removing gradients and shadows and by decreasing the contribution of the outside indirect illumination of the shelter walls and its fluctuations. A significant increase of the light flux will also reduced the integration time and thus, the acquisition time. It will also greatly improve the signal to noise ratio of the hyperspectral dataset and thus provide better results. A measurement of the profile of the cross-track illumination intensity should also improve the photometric correction of the hyperspectral images.

The quality of the classification of the pigments and their efficient separation in distinct classes is strongly dependent on the quality of the measurements. Indeed, even if the ICA transformation efficiently segregates most of the hyperspectral image noise, a higher signal-to-noise ratio of the measurement and a more homogeneous illumination, in particular at small spatial scale (high frequency spatial fluctuation of the reflected light at the millimetre scale), should strongly help in reducing the pixels missed or mixed by the classification tool as well as reducing its false detections. More distinct classes with better defined outlines should result. In particular this will be helpful for classes that depict very faint pigments, which are currently still difficult to separate in classes which did not contain numerous rock pixels.

The choice of the statistical analysis and classification algorithms can also critically affect the final results in terms of pigment classes and ability to separate them. But, as demonstrated by Schmitt et al. (2022), ICA appears the most efficient to separate pigments with weak spectral variations or covering only limited area, contrary to the PCA and MNF algorithms. However, a high signal-to-noise ratio is needed to properly classify some of the faintest painted figures as they have little spectral contrast with the surrounding rock wall. The simple supervised SAM classification tool is also showing its limits for separating classes with small differences. More advanced tools need to be tested to estimate whether better classification results can be obtained and at what complexity cost. The presence of specific minerals has been established from the SWIR data, but this identification still needs to be done for the pigments, a more complex task that will need the combined use of the VNIR & SWIR data together with complementary in-situ and laboratory analyses. Also, higher resolution VNIR+SWIR spectra (point field spectrometer) to be acquired at the specific locations of both the ICA end-members and the in-situ analyses will allow to link these analyses with the hyperspectral data and extrapolate them to the entire set of measurements of the painted wall.

V. Conclusion

The results presented in this article are the outcome of tests carried out in the autumn of 2021 with the aim of evaluating the potential contributions of the method to the understanding of schematic expression and the scientific problems mentioned above. These contributions are now unquestionable and demonstrate that the use of both visible and infrared hyperspectral imagery in rock art studies is powerful and reveal new and complementary information.

Upstream of the site study, hyperspectral imaging and its analysis tools allows a better recording and separation of the painted figures covering the walls, some of which are currently invisible to the naked eye, remain invisible after DStretch enhancement or are covered with concretions. It also allows for a better recording and understanding of weathering crusts. The wall study based on hyperspectral imaging acquisitions thus provides a solid basis for the integrated/interdisciplinary study that rock art sites require. From the point of view of iconographic analysis, hyperspectral imaging and the increased knowledge of the graphic repertoire that it allows, permits a more precise contextualisation of graphic expressions. Its contribution also becomes essential to the understanding of the construction of graphic space and the structures of iconography, whether syntactic and/or chronological, which are themselves essential to the study and understanding of the cognitive nature of this graphic expression. As for the analysis of the colouring matter, it thus acquires a spatial dimension which must however be completed by specific in situ or laboratory analyses that hyperspectral imaging will also allow to orientate. Hyperspectral imaging, by providing information on the form and composition of the iconography, but also on the evolution and preservation of the rock wall, appears to be a method at the interface of the various disciplines involved in the integrated study of painted shelters.

Statements and declarations

Funding

This work was financed by the IDEX Université Grenoble Alpes in the framework of the COPRA project (Matières COlorantes, temps et PRatiques de l'Art pariétal néolithique/ Colouring matter, time and practice in Neolithic rock art. dir. C. Defrasne).

Conflicts of interest

Not applicable

Ethics approval/declaration

Not applicable

Consent to participate

Not applicable

Consent for publication

All authors consent to the publication of this article.

Availability of data and material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability (software application or custom code)

Not applicable

Authors' contributions

The acquisition of hyperspectral imagery in the field was carried out by M.M., M.G. and D.F. as part of an archaeological project led by C.D.
The processing of hyperspectral data was carried out by M. M. and B. S.
C.D., B.S., M.M., S.L.M., M.G., E.C. wrote the main manuscript text.
C.D. prepared figures 1 to 4, 8, 15
C.D. and M.M. prepared figures 5, 6, 7, 9, 10, 11
B.S. prepared figures 12, 13, 14 and 16.
All authors reviewed the manuscript.

Acknowledgments

We would like to thank the municipality of Saint-Rémy-de-Provence and the Service Régional d'Archéologie de Provence Alpes Côte d'Azur for granting us permission to work on the Otello site. We would also like to thank the people who helped us with the fieldwork that led to the results presented here, and in particular the porters who made it possible to transport the material.

References

Alexopoulou A, Kaminari A, Moutsatsou A (2019) Multispectral and Hyperspectral Studies on Greek Monuments, Archaeological Objects and Paintings on Different Substrates. Achievements and Limitations. Communications in Computer and Information Science. https://doi.org/10.1007/978-3-030-12960-6_31

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 Spectrometry 48:262–273. https://doi.org/10.1002/xrs.2951

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. Microchemical Journal 395. https://doi.org/10.1016/j.microc.2018.05.050

Bayarri Cayón V (2020) Algoritmos de análisis de imágenes multiespectrales e hiperespectrales para la documentación e interpretación del arte rupestre. Universidad Nacional de Educación a Distancia (España). Escuela Internacional de Doctorado. Programa de Doctorado en Tecnologías Industriales. 2020.

Bayarri V, Latova J, Castillo E, et al (2015) Nueva documentación y estudio del arte empleando técnicas hiperespectrales en la Cueva de Altamira

Bayarri-Cayón V, Castillo-López E, Antonio J (2016) An Automatic Approach for documentation and recovery of rupestrian paintings using Multispectral Remote Sensing. 7

Bayarri V, Sebastián MA, Ripoll S (2019) Hyperspectral Imaging Techniques for the Study, Conservation and Management of Rock Art. Applied Sciences 9:5011. https://doi.org/10.3390/app9235011

Bayarri V, Castillo E, Ripoll S, Sebastian MA (2021) Improved Application of Hyperspectral Analysis to Rock Art Panels from El Castillo Cave (Spain). applied science 11:1292

Borengasser M, Hungate WS, Watkins R (2007) Hyperspectral Remote Sensing: Principles and Applications. CRC Press, Boca Raton

Catelli E, Randeberg L, Strandberg H, et al (2018) Can hyperspectral imaging be used to map corrosion products on outdoor bronze sculptures? J Spectral Imaging a10. https://doi.org/10.1255/jsi.2018.a10

Chalmin E, Schmitt B, Chanteraud C, et al (2021) How to distinguish red coloring matter used in prehistoric time? The contribution of visible near-infrared diffuse reflectance spectroscopy. Color research and application 46:656–673

Cortea IM, Ratoiu L, Ghervase L, et al (2021) Investigation of Ancient Wall Painting Fragments Discovered in the Roman Baths from Alburnus Maior by Complementary Non-Destructive Techniques. Applied Sciences 11:10049. https://doi.org/10.3390/app112110049

Cucci C, Delaney JK, Picollo M (2016) Reflectance Hyperspectral Imaging for Investigation of Works of Art: Old Master Paintings and Illuminated Manuscripts. Acc Chem Res 49:2070–2079. https://doi.org/10.1021/acs.accounts.6b00048

Cucci C, Picollo M, Chiarantini L, et al (2020) Remote-sensing hyperspectral imaging for applications in archaeological areas: Non-invasive investigations on wall paintings and on mural inscriptions in the Pompeii site. Microchemical Journal 158:105082. https://doi.org/10.1016/j.microc.2020.105082

Cucci C, Webb EK, Casini A, et al (2019) Short-wave infrared reflectance hyperspectral imaging for painting investigations: A methodological study. Journal of the American Institute for Conservation 58:16–36. https://doi.org/10.1080/01971360.2018.1543102

Daniel F, Mounier A (2015) Mobile hyperspectral imaging for the non-invasive study of a mural painting in the Belves Castle (France, 15th C). STAR: Science & Technology of Archaeological Research 1:81–88. https://doi.org/10.1080/20548923.2016.1183942

Daniel F, Mounier A, Pérez-Arantegui J, et al (2017) Comparison between non-invasive methods used on paintingsby Goya and his contemporaries: hyperspectral imagingvs. point-by-point spectroscopic analysis. Analytical and bioanalytical chemistry 409:4047–4056

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 in Analytical Chemistry 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. Microchemical Journal 155:104674. https://doi.org/10.1016/j.microc.2020.104674

Defrasne C (2014) Digital image enhancement for recording rupestrian engravings: applications to an alpine rockshelter, Journal of Archaeological Science. Journal of Archaeological Science 50:5031–5038

Defrasne C, Chalmin E, Bellot-Gurlet L, Thirault E (2019) From archaeological layers to schematic rock art? Integrated study of the Neolithic coloring materials on an alpine rock art site. Archaeological and Anthropological Sciences 11:6065–6091

Defrasne C, Massé M, Giraud M, et al (2021) L’abri Otello (Saint-Rémy-de-Provence, Bouches-du-Rhône). SRA PACA

Domingo I, Villaverde V, Lopez-Montalvo E, et al (2013) Latest developments in rock art recording: towards an integral documentation of Levantine rock art sites combining 2D and 3D recording techniques. Journal of Archaeological Science 40:1879–1889. https://doi.org/10.1016/j.jas.2012.11.024

Fischer C, Kakoulli I (2006) Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications. Studies in Conservation 51:3–16

Frati G, Launeau P, Robin M, Giraud M, Juigner M, Debaine F, Michon C. Coastal Sand Dunes Monitoring by Low Vegetation Cover Classification and Digital Elevation Model Improvement Using Synchronized Hyperspectral and Full-Waveform LiDAR Remote Sensing. *Remote Sensing*. 2021; 13(1):2 rati G, Launeau P, Robin M, Giraud M, Juigner M, Debaine F, Michon C. Coastal Sand Dunes Monitoring by Low Vegetation Cover Classification and Digital Elevation Model Improvement Using Synchronized Hyperspectral and Full-Waveform LiDAR Remote Sensing. *Remote Sensing*. 2021; 13(1):29. 9.

Gabasova L.R., Schmitt B., Grundy W., Bertrand T., Olkin C.B., Spencer J.R., Young L.A., Ennico K, Weaver H.A., Stern S.A. (2021) Global compositional cartography of Pluto from intensity-based registration of LEISA data. Icarus, 356, 113833,

Hameau P (2002) Passage, transformation et art schématique : l’exemple des peintures néolithiques du sud de la France. Archaeopress, Oxford

Hameau P (2011) Des signes dans l’espace : l’abri Otello à Saint-Rémy-de-Provence. In: Sénépart I, Perrin T, Bonnardin S (eds) Marges, frontières et transgression. Actualité de la recherche. Actes des 8e Rencontres Méridionales de Préhistoire Récente, Marseille, 7 et 8 novembre 2008., Archives d’Ecologie Préhistorique. Toulouse, pp 345–358

Harman J (2005) Using Decorrelation Stretch to ENhance rock art IMages. https://www.dstretch.com/AlgorithmDescription.html. Accessed 24 Nov 2022

Hyvärinen A, Oja E (2000) Independent component analysis: algorithms and applications. Neural Networks 13:411–430. https://doi.org/10.1016/S0893-6080(00)00026-5

Jones C, Duffy C, Gibson A, Terras M (2020) Understanding multispectral imaging of cultural heritage: Determining best practice in MSI analysis of historical artefacts. Journal of Cultural Heritage 45:339–350. https://doi.org/10.1016/j.culher.2020.03.004

Khan MJ, Khan HS, Yousaf A, et al (2018) Modern Trends in Hyperspectral Image Analysis: A Review. IEEE Access 6:14118–14129. https://doi.org/10.1109/ACCESS.2018.2812999

Kim MH, Rushmeier H (2011) Radiometric characterization of spectral imaging for textual pigment identification. In: Proceedings of the 12th International conference on Virtual Reality, Archaeology and Cultural Heritage. Eurographics Association, Goslar, DEU, pp 57–64

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

Le Mouélic S., Rodriguez S., Robidel R., Rousseau B., Seignovert B., Sotin C., Barnes J.W., Brown R.H., Baines K.H., Buratti B.J., Clark R.N., Nicholson P.D., Rannou P., Cornet T. (2018). Mapping polar atmospheric features on Titan with VIMS: From the dissipation of the northern cloud to the onset of a southern polar vortex. Icarus, 311, 371_383.

Le Quellec J-L, Defrasne C, Duquesnoy F (2015) Digital image enhancement with DStretch: is complexity always necessary for efficiency ? Digital Applications in Archaeology and Cultural Heritage 2:

Le Quellec J-L, Harman J, Defrasne C, Duquesnoy F (2013) DStretch et l'amélioration des images numériques. Cahiers de l'AARS 16:177–198

Li GH, Chen Y, Sun XJ, et al (2020) An automatic hyperspectral scanning system for the technical investigations of Chinese scroll paintings. Microchemical Journal 155:104699. https://doi.org/10.1016/j.microc.2020.104699

Liang H (2012) Advances in multispectral and hyperspectral imaging for archaeology and art conservation. Appl Phys A 106:309–323. https://doi.org/10.1007/s00339-011-6689-1

Martinez Garcia J, Hernandez Perez MS (2013) Arte rupestre esquematico en la Peninsula Ibérica, Ayuntamiento de Velez-Blanco

Massé M., Bourgeois O., Le Mouélic S., Verpoorter C., Spiga A., Le Deit L. (2012). Wide distribution and glacial origin of polar gypsum on Mars. Earth and Planetary Science Letters, vol. 317–318, 44-55.

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. Heritage Science 5:43. https://doi.org/10.1186/s40494-017-0157-y

Nicoud E, Palmerini G, Villa V, et al (2022) Géoarchéologie en contexte karstique dans la Maiella (Abruzzes, Italie). Bulletin archéologique des Écoles françaises à l'étranger

Peyghambari S., Zhang Y. (2021). Hyperspectral remote sensing in lithological mapping, mineral exploration, and environmental geology: an updated review. J. Appl. Rem. Sens. 15(3) 031501.

Quesada Martínez E (2008) Aplicación Dstretch del software Image-J. Avance de resultados en el Arte Rupestre de la Región de Murcia. Cuadernos de arte rupestre: revista del Centro de Interpretación de Arte Rupestre de Moratalla 9–27

Ripoll S, Bayarri V, Castillo E, et al (2015) El Panel de las Manos de la Cueva de El Castillo (Puente Viesgo, Cantabria.

Ripoll S, Bayarri V, Muñoz FJ, et al (2021) Hands Stencils in El Castillo Cave (Puente Viesgo, Cantabria, Spain). An Interdisciplinary Study. Proceedings of the Prehistoric Society 87:51–71. https://doi.org/10.1017/ppr.2021.11

Sandak J, Sandak A, Legan L, et al (2021) Nondestructive Evaluation of Heritage Object Coatings with Four Hyperspectral Imaging Systems. Coatings 11:244. https://doi.org/10.3390/coatings11020244

Schmitt B, Bollard Ph, Albert D, et al (2018) SSHADE: "Solid Spectroscopy Hosting Architecture of Databases and Expertise" and its databases. OSUG Data Center Service/Database Infrastructure. https://doi.org/Doi: https://doi.org/10.26302/SSHADE

Schmitt B, Souidi Z, Duquesnoy F, Donzé F-V (2022) From RGB camera to Hyperspectral imaging: a major breakthrough in Neolithic Rock Painting analysis. Archaeological and Anthropological Sciences