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Dominique Lafon-Pham, Stéphane Konik, Julien Monney. On-site spectroradiometric analysis of Palaeolithic cave art: Investigating colour variability in the red rock art of Points cave (France). *Journal of Archaeological Science: Reports*, 2022, 42, pp.103384. 10.1016/j.jasrep.2022.103384 . hal-03593512

**HAL Id: hal-03593512**

**<https://imt-mines-ales.hal.science/hal-03593512>**

Submitted on 22 Jul 2024

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# 1 On-site Spectroradiometric Analysis of Palaeolithic Cave Art: Investigating 2 Colour Variability in the Red Art of Points Cave (France)

3

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11

## 12 **Abstract**

13 The colour of Palaeolithic cave art is an important parameter to consider when examining  
14 possible links between different pieces of rock art. Recent developments in portable, non-  
15 invasive spectroradiometry have given researchers the ability to carry out in-situ  
16 colorimetric analyses of rock art, even in deep-cave environments. Although these methods  
17 provide quantitative data that can be used to compare the colours of different paintings,  
18 differences in chromaticity values can be difficult to interpret from an archaeological point  
19 of view.

20 We investigated factors that may contribute to this colour variability by combining a series  
21 of visible spectroradiometric analyses of the Palaeolithic red rock art in Points Cave  
22 (Aiguèze, France) with macrophotography of the surfaces analysed. This fieldwork was  
23 supplemented by laboratory experiments to produce reference data we could use to assess  
24 the impact of environmental factors on the results of the in-situ spectroradiometric  
25 analyses.

26 The variability in the chromaticity values we obtained can be explained almost entirely by  
27 colour differences in the underlying cave wall and by the extent to which the pigment layer  
28 masks the substrate. These results suggest that the rock art in Points Cave is homogenous  
29 in colour and support the hypothesis suggested by archaeological analyses that the rock art  
30 belongs to a single prehistoric iconographic project.

31

## 32 **Keywords**

33 Spectroradiometry, colorimetry, colouring matter, non-invasive analysis, rock art,  
34 Palaeolithic cave art, Ardeche Gorge

35

36

37

## 38 **1. Introduction: Spectroradiometry as a tool for studying Palaeolithic cave art**

39 Palaeolithic cave art is one of the most fragile forms of cultural heritage. Like the nature of  
40 prehistoric markings on portable objects (e.g., d'Errico et al., 2011), colour is an important  
41 parameter to take into account when documenting, studying and conserving rock art  
42 (Vouvé et al., 2000; de Balbín Behrmann et al., 2009; del Hoyo-Meléndez, 2015; Bednarik,

43 2017; Molada-Tebar et al., 2019; Molada Tebar, 2020; Carrión-Ruiz et al., 2021). However,  
44 simple visual descriptions of colours are too subjective to provide precise descriptions of  
45 rock art figures or to allow comparisons of paintings in different locations, on rock walls of  
46 different colours and/or surface states and/or viewed under different lighting conditions  
47 (Ruiz and Pereira, 2014).

48 Recent technological advances have led to the development of portable, non-invasive  
49 analysis methods, such as spectroradiometry, that can be used in-situ to obtain quantitative  
50 determinations of a piece of prehistoric rock art's colour without impacting its integrity  
51 (e.g., Paillet, 2014). Although they do not provide direct information about a pigment's  
52 mineralogical composition (but see Chalmin et al., 2021), these colorimetric measurements  
53 allow researchers to test hypotheses, based on iconographic, thematic and technical  
54 analyses, about an object's relationship with other objects. They can also be used to  
55 compare the colours of different pieces of rock art, to discuss these results alongside data  
56 acquired using other methods (e.g., SEM-EDX, PIXE, XRF,  $\mu$ Raman, diffractometry, etc.;  
57 e.g., Beck et al., 2012, 2014a, 2014b; Chalmin et al., 2003; Cuñat et al., 2008; Gay et al., 2015;  
58 Hernanz et al., 2012; Lahlil et al., 2012; Lofrumento et al., 2012; Touron et al., 2017;  
59 Westlake et al., 2012) and to read complex superimpositions of rock art or rock art that is  
60 evanescent due to its alteration (Bayarri-Cayón et al., 2016).

61 In-situ spectroradiometric analyses of rock art in the visible spectrum (Konik and Lafon-  
62 Pham, 2018) and in a hyperspectral range that also includes the near infrared (Bayarri et al.,  
63 2019) have shown the contribution this technique can make to studies of Palaeolithic cave  
64 art. When carried out in controlled lighting, spectroradiometric analyses provide an optical  
65 signature for the object's surface that can be used to obtain a standardised expression of  
66 the colour properties (under photopic conditions). Taking into account the geometry and  
67 characteristics of the rock wall (colour, surface conditions, evolution, alteration processes),  
68 it is possible to determine whether differences between optical signatures are due to  
69 differences in the colouring matter's colorimetry. The colour of a piece of rock art on a cave  
70 wall depends on several factors, including: (a) the mineralogical composition of the  
71 colouring matter, (b) the sizes and shapes of the grains constituting this colouring matter,  
72 (c) the arrangement of the grains within the deposited matter, (d) the surface condition of  
73 the rock art, (e) its moisture content and (f) the colour of the underlying wall (Elias et Lafait,  
74 2006). Some of these factors are inherent to the colouring matter; others depend on the  
75 way it was applied to the wall during prehistory and on any pre- and/or post-rock art  
76 alteration processes (e.g., leaching due to water flow, calcite overlay, etc.). The cave wall's  
77 moisture state also has a significant impact on rock art's optical behaviour (Monnard et al.,  
78 2016; Garay et al., 2016; Konik and Lafon-Pham, 2018). Consequently, interpretations of  
79 spectroradiometric data obtained in natural environments must take these factors into  
80 consideration.

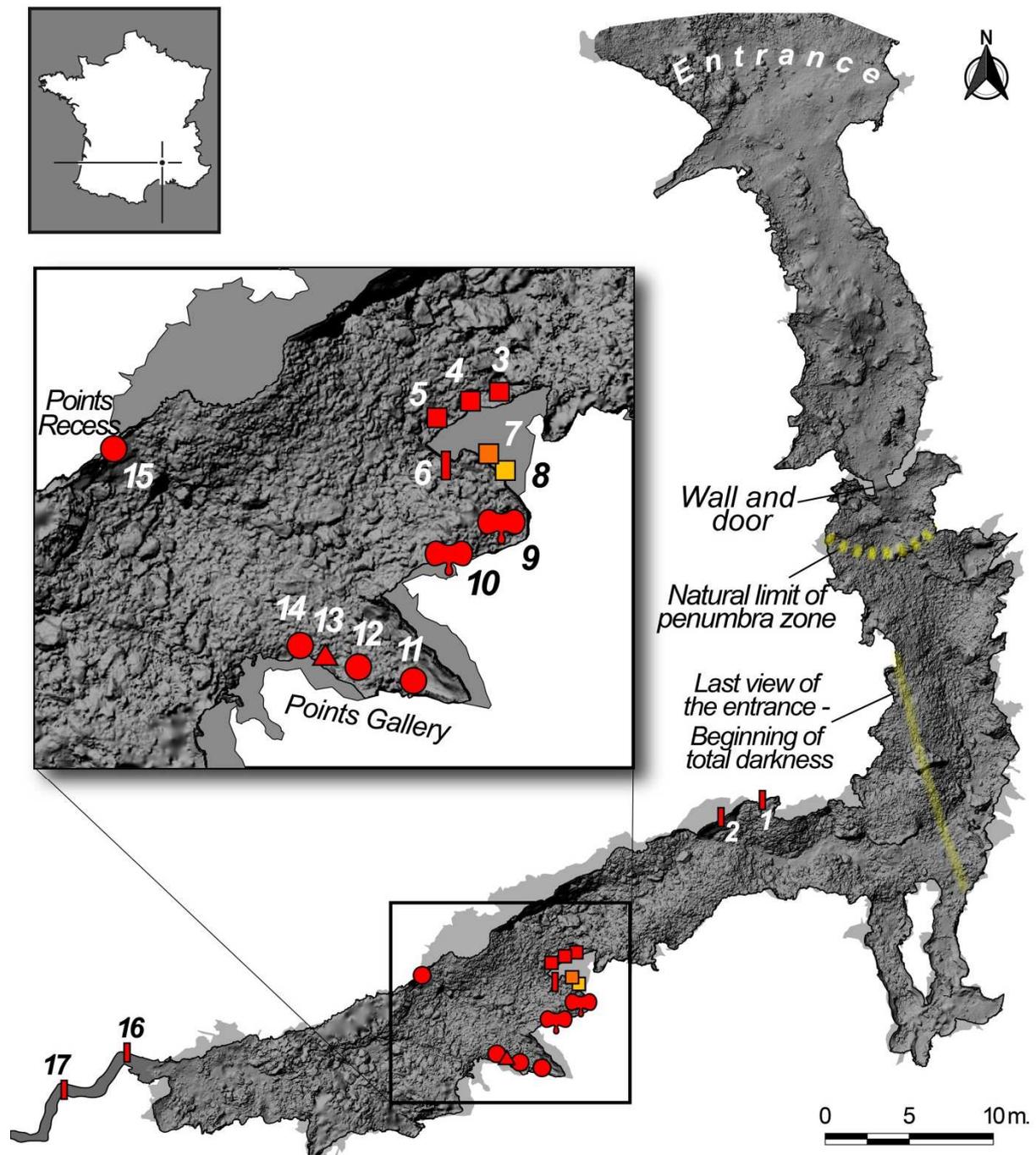
81 With this in mind, and to obtain quantitative measurements we could use to compare the  
82 colorimetric properties of different pieces of Palaeolithic rock art within a cave, we carried  
83 out an extensive spectroradiometric survey in the visible spectrum (380 to 780 nm) of the

84 rock art in Points Cave (Aiguèze, France). The rock art in Points Cave comprises a relatively  
85 small number (72) of paintings and drawings (Monney, 2018b), but they cover a wide range  
86 of iconography (animals, signs, dots), subjects (ibexes, horse, bison) and techniques (dry-  
87 pigment drawing, finger painting, palm printing). Consequently, Points Cave is particularly  
88 suitable for measuring the colorimetric characteristics of all the pieces of rock art within a  
89 single site and examining the factors responsible for possible variations between them.

90

## 91 **2. Points Cave: Setting and Issues**

92 Points Cave is a Palaeolithic rock art cave in the central part of the Ardèche Gorge (France).  
93 Since 2011, it has been the subject of interdisciplinary research as part of the *Datation*  
94 *Grottes Ornées* (Cave Art Dating) project, coordinated by Monney (2018a). The rock art,  
95 which was discovered in 1993 (Brunel et al., 2008, 2018), has numerous iconographic  
96 similarities with the art in the entrance sectors of Chauvet-Pont-d'Arc Cave (Monney,  
97 2018b). All 72 red drawings and paintings in Points Cave occur within a single area,  
98 approximately 75 metres from the cave entrance (Figure 1). Due to the topography of Points  
99 cave (entrance facing north, length of the cave, presence at midway of a 90° curve), all of  
100 them are far beyond the reach of any natural light (Figure 1). They comprise five animal  
101 figures (3 ibexes, 1 horse, 1 bison), five indeterminate tracings, two bi-lobed signs,  
102 one open-angle sign and four clusters containing a total of 59 dots produced by pressing  
103 pigment-covered palms onto the rock.

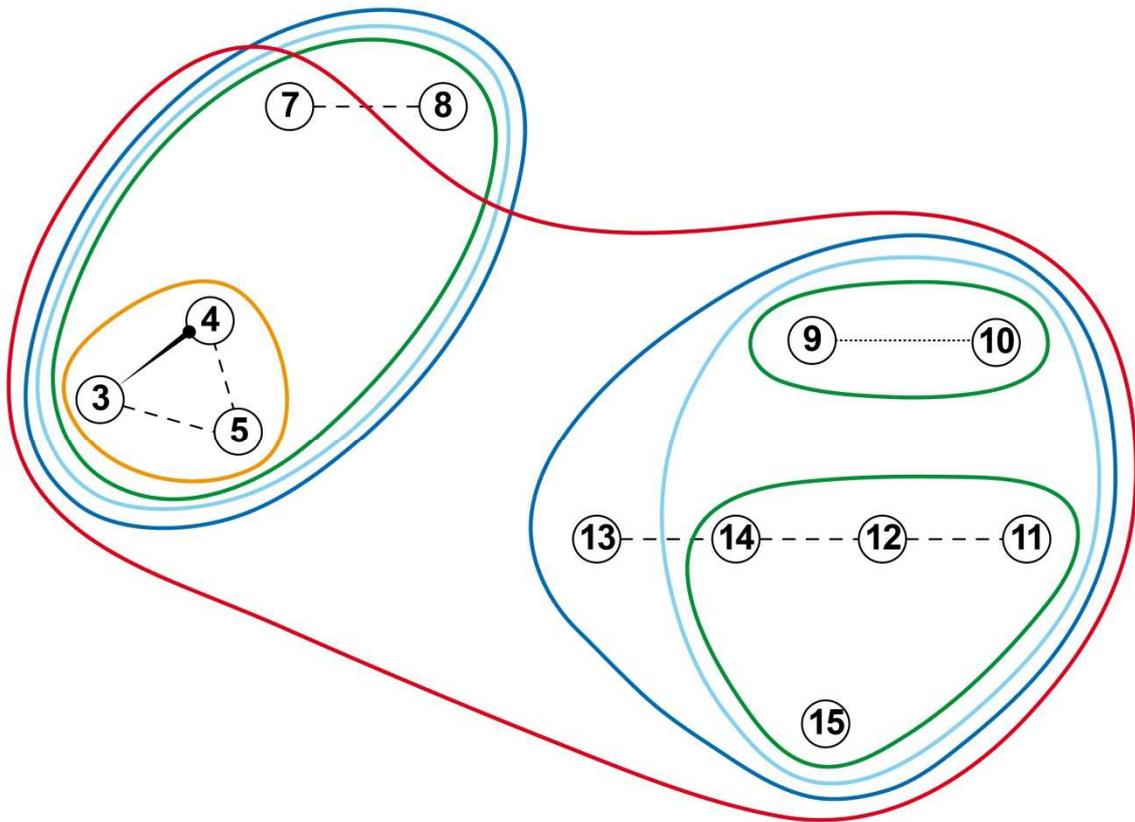


104  
105  
106  
107

**Figure 1:** Topographic map of Points Cave showing the position of the rock art (3D digital credits: S. Jaillet, Edytem).

108 Although the rock art in Points Cave is diverse and occurs in spatially distinct clusters,  
109 archaeological analyses suggest that it consists of two iconographically, technically and  
110 structurally coherent groups (Figure 2): a group of animal figures and a group containing the  
111 palm-printed dots, bi-lobed signs and open-angle sign. However, given the presence of  
112 similar associations of themes, techniques and positioning rules in other rock art caves, such  
113 as the Roc-de-Vézac (Vézac, Dordogne, France; Aujoulat, 1984) and especially some areas

114 of Chauvet Cave (Chauvet et al., 1995; Gély, 2005), the two groups at Points Cave may  
 115 belong to a single prehistoric iconographic project (Monney, 2018b).  
 116



**CAPTION**

(n) Rock Art – inventory number

**Structural Links**

- Scene
- Unilateral scenic link
- Bilateral scenic link
- ..... Serial repetition
- - - Spatial proximity (same panel)

**Similarity Envelopes**

- Iconography**
  - Animal Figure (no. 3,4,5,7,8)
  - Bi-lobed Sign (no. 9,10)
  - Palm dot cluster (no. 11,12,14,15)
  - Open-angle Sign (no. 13)
- Themes**
  - Ibex (no. 3,4,5)
  - Horse (no. 7)
  - Bison (no. 8)
- Technique 1 (Pigment phase)**
  - Wet (painting) (no. 9,10,11,12,13,14,15)
  - Dry (drawing) (no. 3,4,5,7,8)
- Technique 2 (Application mode)**
  - Drawing (no. 3,4,5,7,8)
  - Palm printing (no. 9,10,11,12,14,15)
  - Finger painting (no. 13)
- Technique 3 (Colour)**
  - purplish red (no.3,4,5,7,9,10,11,12,13,14,15)
  - reddish-beige (no.8)

117  
 118 **Figure 2:** Diagram showing the characteristics shared by different paintings (similarity  
 119 envelopes and structural links), as suggested by archaeological analysis (after Monney,  
 120 2018b).  
 121

122 Preliminary visual observations also suggested that all the pieces of rock art, except bison 8,  
 123 are the same colour. However, this categorisation into two colour subsets (purplish red and  
 124 reddish-beige) is subjective and contingent on the observation conditions, including  
 125 lighting, colour of the surrounding cave walls and location of the panels (non-adjacent

126 panels cannot be compared directly). Moreover, subsequent in-situ analyses using other  
127 techniques have not provided the data needed to support or reject this archaeology-derived  
128 hypothesis. Notably, a detailed attempt to use in-situ pXRF analysis to determine the  
129 physicochemical composition of the pigments in Points Cave showed this approach's limits  
130 (Chanteraud et al., 2021). Consequently, we decided to determine whether  
131 spectroradiometric measurements could provide useful data for testing archaeological  
132 hypotheses.

133 Would colorimetric measurements support the connections between different pieces of  
134 rock art suggested by archaeological observations, or would they indicate different  
135 connections? Would they bring to light finer distinctions within groups of objects (e.g., sub-  
136 sets within a group of dots)? If so, does an optical signature primarily reflect the colour of  
137 the colouring matter or does it also carry a readable signature of the way the colouring  
138 matter was prepared and applied during prehistory, the nature of the substrate (geometry,  
139 colour, surface conditions) and/or subsequent alteration processes (leaching, covering)? We  
140 addressed these questions by combining a comprehensive, in-situ spectroradiometric  
141 survey of the rock art in Points Cave, carried out in 2018 and 2019, with laboratory  
142 experiments aimed at establishing a reference framework we could use to assess the impact  
143 of environmental factors on our spectroradiometric measurements.

144

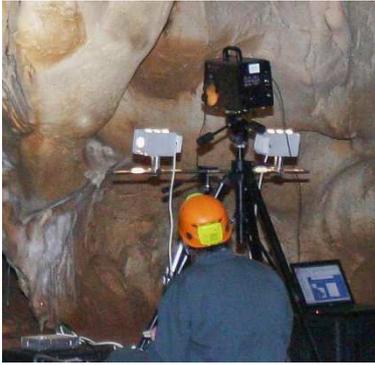
### 145 **3. Methodology**

#### 146 *3.1. Field measurement protocol*

147 We acquired radiance spectra for the rock art in Points Cave by following Konik and Lafon-  
148 Pham's (2018) non-invasive, non-contact experimental protocol (Figure 3). We used a  
149 Konica Minolta CS-2000 portable spectroradiometer, which can detect very low luminance  
150 levels (according to the manufacturer: minimum luminance =  $0.003 \text{ cd/m}^2$  for a  $1^\circ$   
151 measurement angle, accuracy of  $\pm 2\%$ ). It also allows the operator to switch measurement  
152 angles ( $1^\circ$ ,  $0.2^\circ$ , or  $0.1^\circ$ ) to adjust the measurement area to the distance from the target and  
153 the size of the surface under study. The CS-2000 has a spectral range of 380 to 780 nm, with  
154 a data output interval of 1 nm.

155 When taking measurements, we positioned the spectroradiometer so its viewing axis was  
156 perpendicular to the measurement surface and adopted an illumination geometry that was  
157 as close as possible to  $45^\circ/0^\circ$  (sample illumination angle =  $45^\circ$ , measurement angle =  $0^\circ$ , i.e.,  
158 perpendicular to the surface). This configuration minimises specular reflections toward the  
159 spectroradiometer when the measurement surface includes bright calcite or a water film  
160 (detection mainly of the diffuse component of the light signal reflected by the surface being  
161 measured).

162



163  
164  
165

**Figure 3:** View of the spectroradiometer and light sources used *in situ*.

166 Even though the rock drawings are naturally far beyond the reach of direct or indirect  
167 daylight, the door located about 30 m away from the entrance in a masonry wall was kept  
168 closed during the analyses.

169 Measuring the colour of rock art in a natural cave can be difficult due to the irregular  
170 morphology of cave walls and floors and to variations in the art's preservation state.  
171 Although Points Cave is not a particularly difficult cave, the floor is very uneven and  
172 sometimes unstable (scree and boulder piles). Hence, we developed a measurement  
173 strategy that would provide reliable results, even under these conditions.

174 To minimise the amount of non-coloured surface included within each analysis point, we  
175 placed the spectroradiometer as close as possible to the cave wall. Wall-to-  
176 spectroradiometer distances were mostly between 1.06 m and 2.13 m (median  
177 distance = 1.86 m), but the uneven ground and the morphology of the cave walls meant that  
178 some of the rock art measurements had to be made with the spectroradiometer up to  
179 3.02 m from the wall. Accordingly, the analysis points on the wall had diameters of between  
180 3.7 mm and 21.1 mm (median diameter = 10.4 mm). Because data acquisition times at low  
181 light levels are long (up to 2 minutes when the spectroradiometer is far from the wall and  
182 the measurement angle is  $0.1^\circ$ ) and because the spectroradiometer must not move, we  
183 took great care to place the tripod in a stable position.

184 Nevertheless, working underground has certain advantages for this type of measurement.  
185 For example, because deep caves are completely dark, it is possible to fully control the  
186 lighting conditions. For the present study, we used light sources with a continuous and even  
187 spectral power distribution equivalent to daylight (very low UV and IR), with low power and  
188 a colour temperature of 4,700 K. The choice of this type of light source was not intended to  
189 replicate the palaeolithic artists' lighting conditions but was due to its quality (continuous  
190 spectrum, uniform beam, temporal stability) and to its ability to provide a good estimation  
191 of the spectral reflectance. We arranged these light sources at an angle of  $45^\circ$  to the surface  
192 being measured and chose a light beam that was strong enough to correctly illuminate the  
193 surface, even at a great distance (at a distance of 2.4 m: beam diameter of 1.6 m and  
194 illuminance of approx. 230 lux).

195 We analysed every piece of rock art whose colouring matter was sufficiently dense and  
196 whose location allowed the spectroradiometer to be positioned satisfactorily, performing at

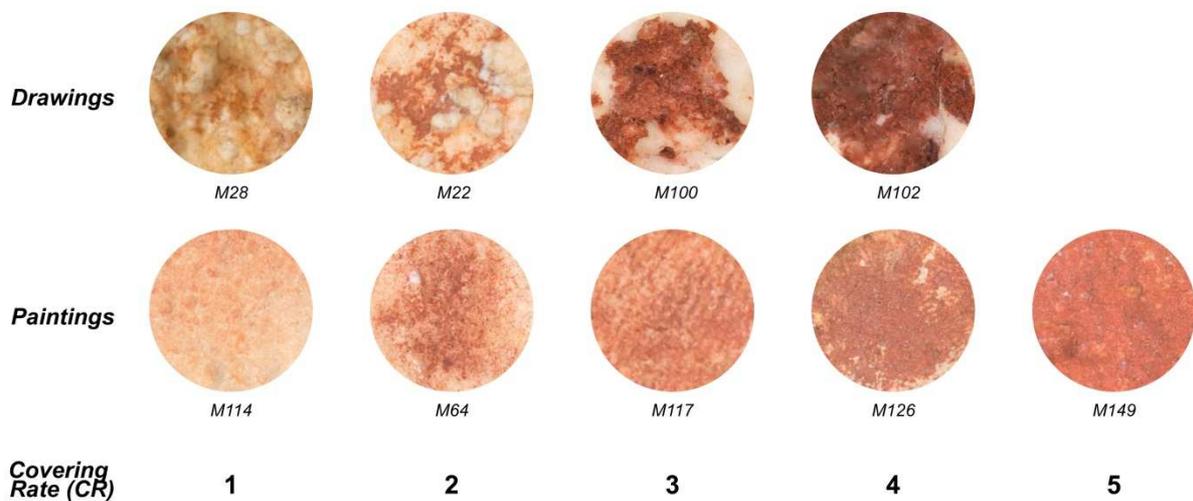
197 least one measurement in the case of the palm dots and between two and  
 198 nine measurements in the case of the other pieces of art (Table 1). Each spectral radiance  
 199 measurement was associated with a measurement on a white target carried out under  
 200 similar positioning and lighting conditions. After calculating the reflectance, the colour was  
 201 expressed using the 2° CIE 1931 standard observer system (CIE: International Commission  
 202 on Illumination), following CIE standard illuminant D65. We chose the illuminant D65 as our  
 203 aim was to identify all the colour variations linked to the red colouring matter, regardless of  
 204 whether they are perceptible or not by an observer in real lighting conditions. All  
 205 measurement locations (undecorated walls and pieces of art) were chosen so they were, as  
 206 far as possible, outside concretion zones.  
 207 Given the high and relatively constant humidity in Points Cave, it is reasonable to assume  
 208 that the colouring matter is always damp and has a reasonably stable moisture content.  
 209 There was no surface water on any of the rock art during the measurement campaigns.  
 210

<b>Animal Figures</b>	<b>Type of rock art (technique used)</b>	<b>34</b>
lbex – no. 3	<i>Drawing (pigment applied dry)</i>	5
lbex – no. 4	<i>Drawing (pigment applied dry)</i>	7
lbex – no. 5	<i>Drawing (pigment applied dry)</i>	2
Horse – no. 7	<i>Drawing (pigment applied dry)</i>	8
Bison – no. 8	<i>Drawing (pigment applied dry)</i>	9
V-shaped sign – no. 8bis (on Bison no. 8)	<i>Drawing (pigment applied dry)</i>	3
<b>Bi-lobed signs</b>		<b>13</b>
Small bi-lobed sign – no.9	<i>Solid painting (palm printing)</i>	4
Large bi-lobed sign – no.10	<i>Solid painting (palm printing)</i>	9
<b>Palm dots</b>		<b>85</b>
Dot cluster – no.11	<i>Solid painting (palm printing)</i>	10
Dot cluster – no.12	<i>Solid painting (palm printing)</i>	13
Dot cluster – no.14	<i>Solid painting (palm printing)</i>	28
Dot cluster – no.15	<i>Solid painting (palm printing)</i>	34
<b>Open-angle sign</b>		<b>3</b>
Open-angle sign – no.13	<i>Painting (finger tracing)</i>	3
<b>Charcoal marks</b>		<b>2</b>
Charcoal mark – Tch 61		1
Charcoal mark – Tch 82		1
<b>Natural cave walls</b>		<b>7</b>
<b>Total</b>		<b>144</b>

212 **Table 1:** Number of spectroradiometric measurements carried out on each type of rock art  
213 and/or surface in Points Cave.

214

215 Finally, we produced a macro-photographic and photogrammetric record of the areas we  
216 analysed and recorded the position of each analysis point on each piece of rock art. We used  
217 3D macro-photographic models to determine the exact proportion of each analysis point  
218 covered by colouring matter and to describe each area measured, including the possible  
219 presence of calcite, soot or any other substance. We then assessed the percentage of  
220 underlying substrate covered by the colouring matter, a parameter we named "covering  
221 rate" (CR), and drew up a six-part classification ranging from CR0 (bare substrate with no  
222 colouring matter) to CR5 (covering rate greater than 90%, see Figure 4). This work was an  
223 essential step in interpreting our results.



224

225 **Figure 4:** Chart showing the percentage of underlying substrate covered by the colouring  
226 matter, with examples of each covering rate for the line drawings (animal figures) and the  
227 solid paintings (bi-lobed signs, open-angle sign, palm dots). CR1: < 30%; CR2: 30-50%;  
228 CR3: 50-70%; CR4: 70-90%; CR5: > 90%. None of the drawings we measured had a CR of  
229 > 90%.

230

231 We also performed a series of laboratory experiments to obtain reference data we could use  
232 to assess the impact of intrinsic and environmental factors on the chromaticity values  
233 provided by the in-situ spectroradiometry analyses. These factors include variations in the  
234 colour layer (covering rate, surface condition, thickness) and in the mineralogical  
235 composition of the colouring matter.

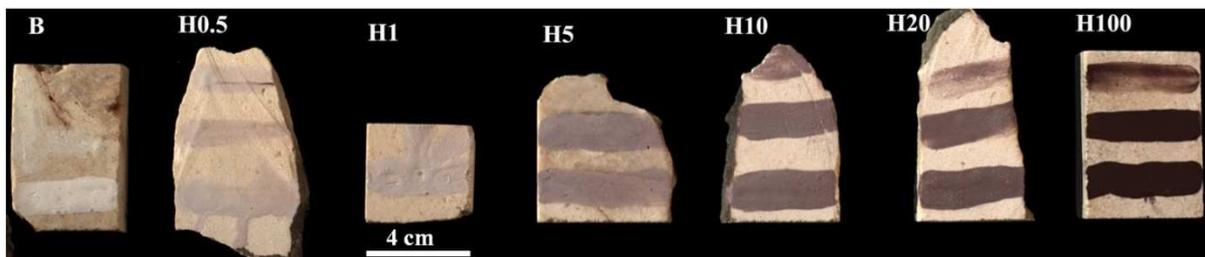
236 As the precise origin of the colouring matter used in Points Cave during the Upper  
237 Palaeolithic has not yet been identified (Chanteraud, 2020), we conducted our experiments  
238 on mixtures of minerals commonly found in the materials used to make Upper Palaeolithic  
239 cave art, that is, kaolin and calcium carbonate, for the base material, and hematite (red iron  
240 oxide), for the pigment. We created seven different mixtures of these minerals, which we  
241 suspended in water and applied to sawn Urganian limestone blocks (similar to the limestone

242 of Points Cave). We adapted the amount of water used in each mixture in order to achieve a  
 243 rheological behaviour compatible with the application mode chosen for the experiment  
 244 (pseudoplastic behaviour). The base material, a blend of kaolin (78% by mass) and calcium  
 245 carbonate (22% by mass), was the same for all the mixtures tested (Table 2).  
 246

	<b>Hematite</b> (% by mass)	<b>Kaolin</b> (% by mass)	<b>Calcium carbonate</b> (% by mass)
Non-coloured base ( <b>B</b> )	0	78	22
Hematite 0.5% ( <b>H0.5</b> )	0.5	77.61	21.89
Hematite 1% ( <b>H1</b> )	1	77.22	21.78
Hematite 5% ( <b>H5</b> )	5	74.1	20.9
Hematite 10% ( <b>H10</b> )	10	70.2	19.8
Hematite 20% ( <b>H20</b> )	20	62.4	17.6
Hematite 100% ( <b>H100</b> )	100	0	0

247 **Table 2:** Mineralogical composition of the colour mixtures used in the application and  
 248 measurement tests. Abbreviations in bold are used to identify the mixtures in the following  
 249 figures.

250  
 251 We used our fingers to paint stripes of each pigment on the limestone blocks, varying the  
 252 quantity of pigment to obtain stripes with different covering rates (Figure 5). Laboratory  
 253 measurements conducted on these blocks provided data for known pigment compositions  
 254 that we could then compare with the results of the colorimetric analyses conducted in  
 255 Points Cave.  
 256



257  
 258 **Figure 5:** Urganian limestone blocks painted with different kaolin-calcium carbonate-  
 259 hematite mixtures, photographed after drying. The hematite concentration of the pigment  
 260 increases from left to right. For each block, the covering rate increases from top to bottom  
 261 (see Table 2 for details of each mixture).

262  
 263 **4. Results**

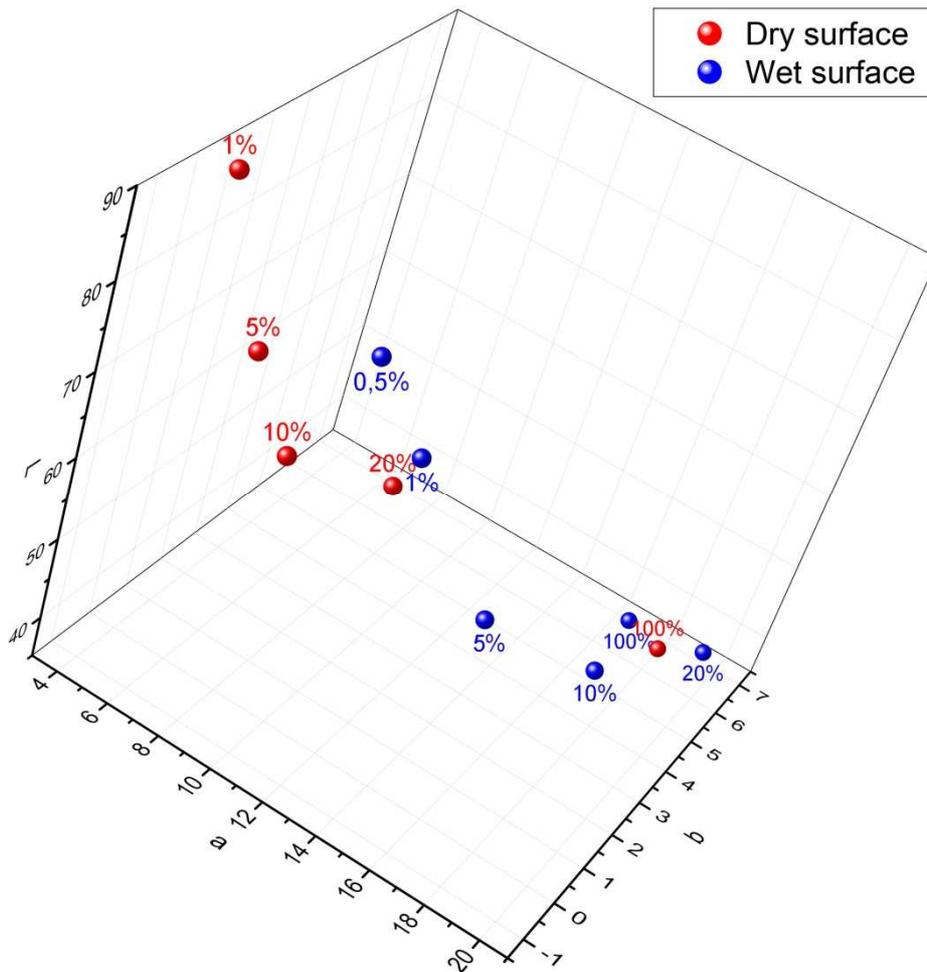
264 *4.1. Field analyses*

265 We conducted 241 radiance analyses in Points Cave. Ninety-five of these analyses were  
266 blank-target measurements; the remaining 146 analyses were conducted on red rock art,  
267 black charcoal marks and surrounding rock walls (Table 1). Eliminating two measurements  
268 (M43 and M60) that were unusable due to technical problems at the time of recording, gave  
269 us a final sample of 144 usable measurements.

270

271 *4.2. Laboratory analyses*

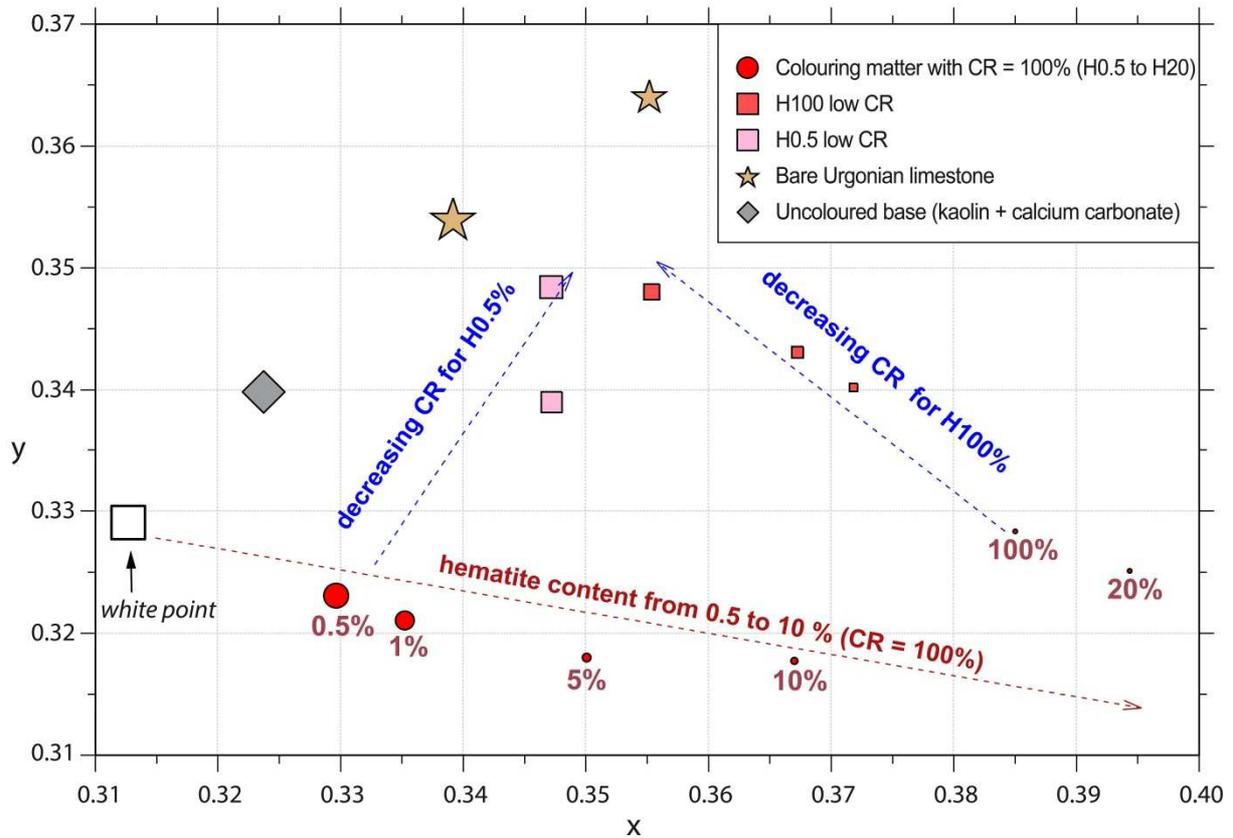
272 We analysed each experimental sample under both wet (limestone block immersed to half  
273 height in a water tank) and dry (limestone block air dried for 15 days) conditions. Plotting  
274 the values obtained on perfectly covered surfaces in CIELab space (D65; 1931 CIE 2°  
275 observer) (Figure 6) showed that adding water to the base + pigment mixtures enhanced  
276 their colour. The colorimetric analyses confirmed the visual impression that the colouring  
277 matter is redder when wet than when dry, as the colour range for the wet measurements  
278 ("a" values up to 20) was wider than the range for the dry measurements. In both cases, the  
279 colour changed from less saturated and lighter to more saturated and darker as the  
280 hematite content increased. Thus, whether the surfaces were wet or dry, the order of the  
281 chromaticity values was the same. The inverted positions of the wet H20 and H100 points is  
282 probably due to a measurement or preparation problem. For example, there may have been  
283 a reflection from a small part of the surface measured, which is not completely flat (specular  
284 reflection contributing to the measured value). Furthermore, differences in the rheological  
285 behaviour of the pure hematite compared with the hematite + base material mixtures, due  
286 to the hematite grains being coarser than the base-material grains, may have produced  
287 differences in the microstructure of the pure hematite pigment layer compared with the  
288 hematite + base material layer (change in the way the grains are arranged).



289  
 290 **Figure 6:** CIE Lab diagram (D65, 1931 CIE 2° observer): Values obtained in the laboratory on  
 291 wet and dry surfaces perfectly covered by colouring matter.

292  
 293 The colouring matter's pigment load determines its tinting strength, with the changes in  
 294 colour being due to changes in absorption phenomena. However, the relationship between  
 295 tinting strength and pigment load is not linear and maximum tinting strength is generally  
 296 attained below 100% pigment load. In our experiments, the colouring matter's tinting  
 297 strength did not increase significantly above a hematite content of approximately 20%. This  
 298 limit could explain the non-alignment of the values for the colouring matter with 20% and  
 299 100% hematite contents (changes in the microstructure of the high hematite content paint  
 300 layer).

301 The chromaticity coordinates of wet material with 100% pigment cover generally lie along a  
 302 single line (Figure 7) and occur in the order of their hematite content, although the  
 303 relationship between a sampling point's position on the line and its hematite content is not  
 304 linear. Values obtained at sampling points with low pigment covering rates deviate from  
 305 this line. As predicted by additive mixing theory (Sève, 1996; Wyszecki and Stiles 2000), the  
 306 values for each pigment composition lie along a separate line between the values for  
 307 perfectly covered substrate and uncovered substrate; values are ordered according to the  
 308 covering rate.



310

311

**Figure 7:** Chromaticity plot (1931 CIE 2° observer, D65) obtained on wet material. The size of the dots is proportional to Y (i.e., luminance: the larger the dot, the lighter the surface measured).

312

313

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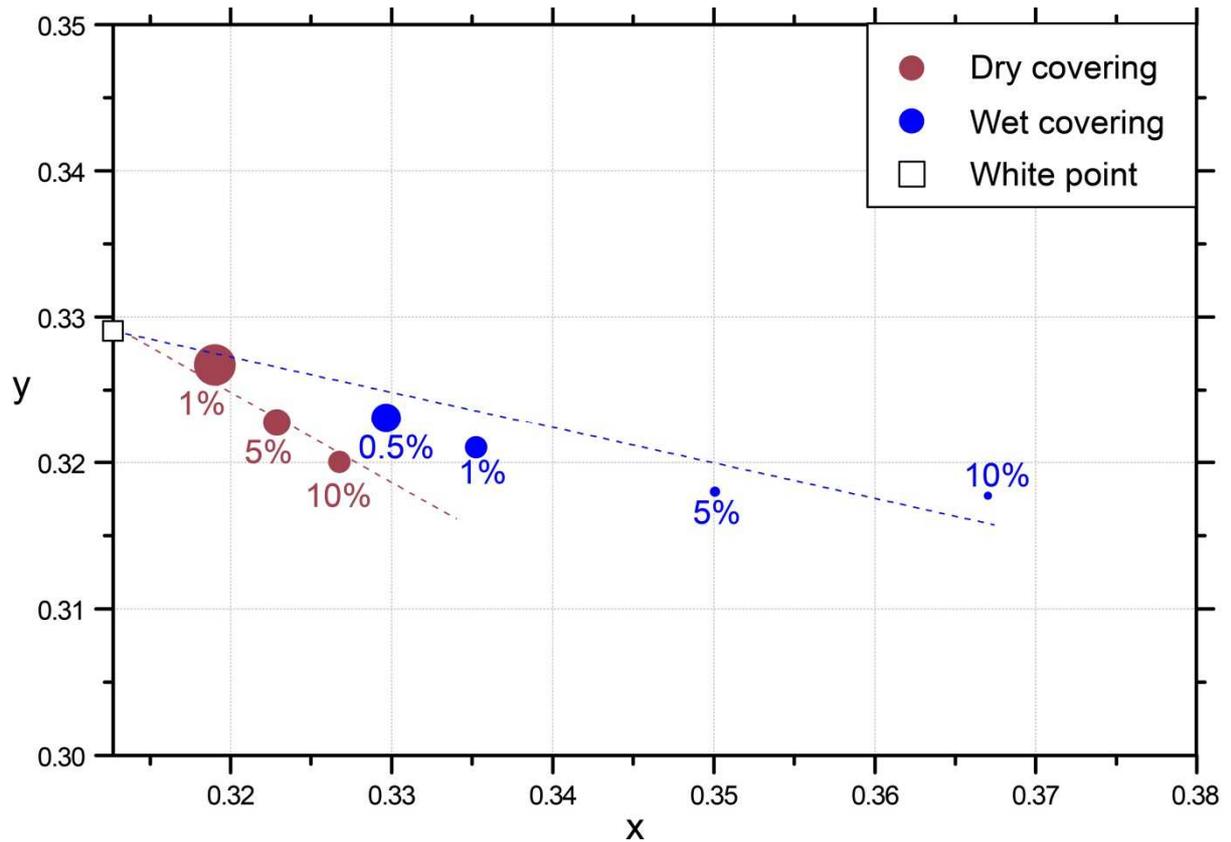
Plotting chromaticity values obtained under wet conditions alongside those obtained under dry conditions clearly illustrates this change in alignment (Figure 8). Differences in colour due to differences in composition appeared more clearly in measurements made under wet conditions.

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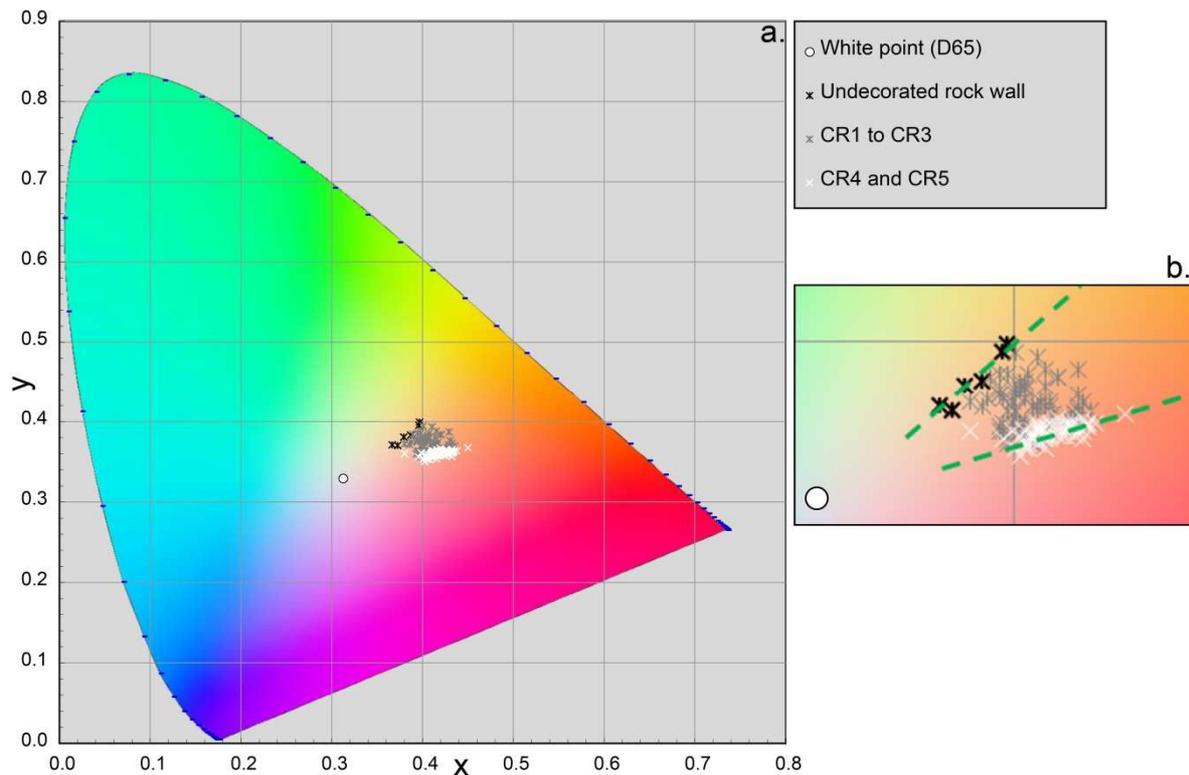
321 **Figure 8:** Plot (1931 CIE 2° observer, D65) of chromaticity coordinates obtained in wet and  
 322 dry conditions. The size of the dots is proportional to Y.

323

### 324 5. Discussion

325 We carried out the in-situ spectroradiometry survey during two separate field campaigns,  
 326 conducted in 2018 and 2019. The absence of variation in the values obtained from one  
 327 campaign to the next shows that the measurement protocol is reliable and replicable. We  
 328 plotted all the measurements made on rock art in Points Cave on a chromaticity diagram  
 329 (Figure 9).

330



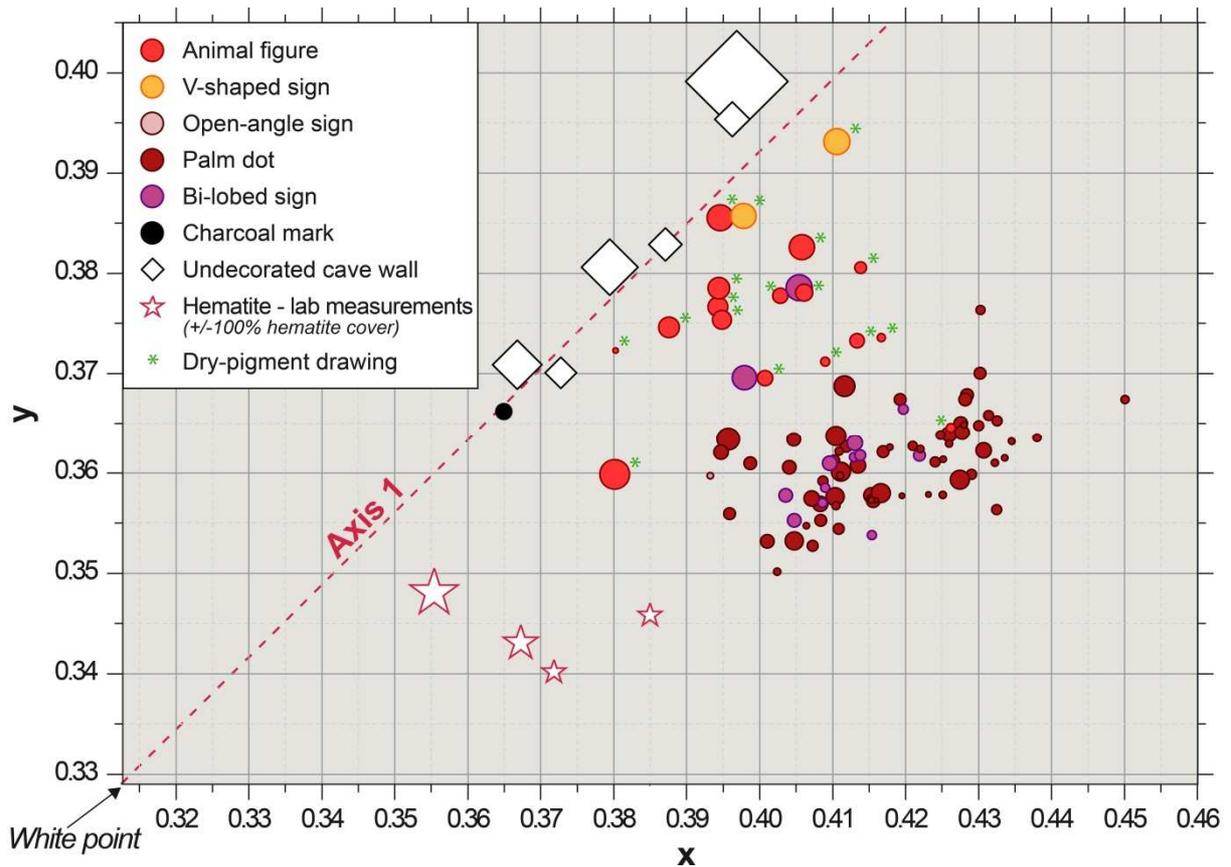
331  
 332 **Figure 9:** a: Chromaticity diagram (D65, 1931 CIE 2° observer) showing the values obtained  
 333 on the rock art and undecorated walls in Points Cave. Fig. 8b: close-up of the area occupied  
 334 by the values. The points are grouped into three classes according to the pigment covering  
 335 rate (see Figure 4).

336

337 *5.1. Variations in the colour of the cave walls*

338 The distribution of the chromaticity coordinates, shown according to the type of surface  
 339 analysed (rock art or undecorated cave wall), reveals several points (Figure 10). First, it  
 340 shows that values obtained on undecorated surfaces (white diamonds) lie along a diagonal  
 341 line (named axis 1), indicating that the natural colour of the cave walls varies between two  
 342 end points. This variation is probably the result of differences in the degree of alteration of  
 343 the limestone surface, but more data on how physical and chemical alteration processes  
 344 (e.g., clay deposition, leaching, concretion) affect cave wall colour would be needed to  
 345 verify this hypothesis.

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**Figure 10:** Section of the chromaticity diagram showing the position of the measurements according to the type of surface analysed (rock art or undecorated cave wall). The size of the dots is proportional to Y.

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### 5.2. Chromaticity coordinates, types of rock art and prehistoric painting techniques

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The plot of chromaticity coordinates also clearly shows two clusters corresponding to two types of rock art (Figure 10). One cluster contains the palm dots and all the signs except for the V-shaped sign on the body of bison 8. The other cluster, which lies closer to the chromaticity coordinates of the cave walls, contains the animal figures. This distribution may be due to a correlation between the chromaticity and the technique used to produce the art (painting vs. drawing), or the way the colouring matter was applied to the walls (printing vs. tracing). Indeed, the open-angle sign, palm dots and bi-lobed signs (lower right-hand part of the graph) are made of solid colour, produced by palm printing (palm dots and bi-lobed signs) or finger tracing (open-angle sign 13), whereas the animal figures and the V-shaped sign on the body of bison 8 are line drawings.

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### 5.3. Relationship between chromaticity coordinates and pigment covering rates

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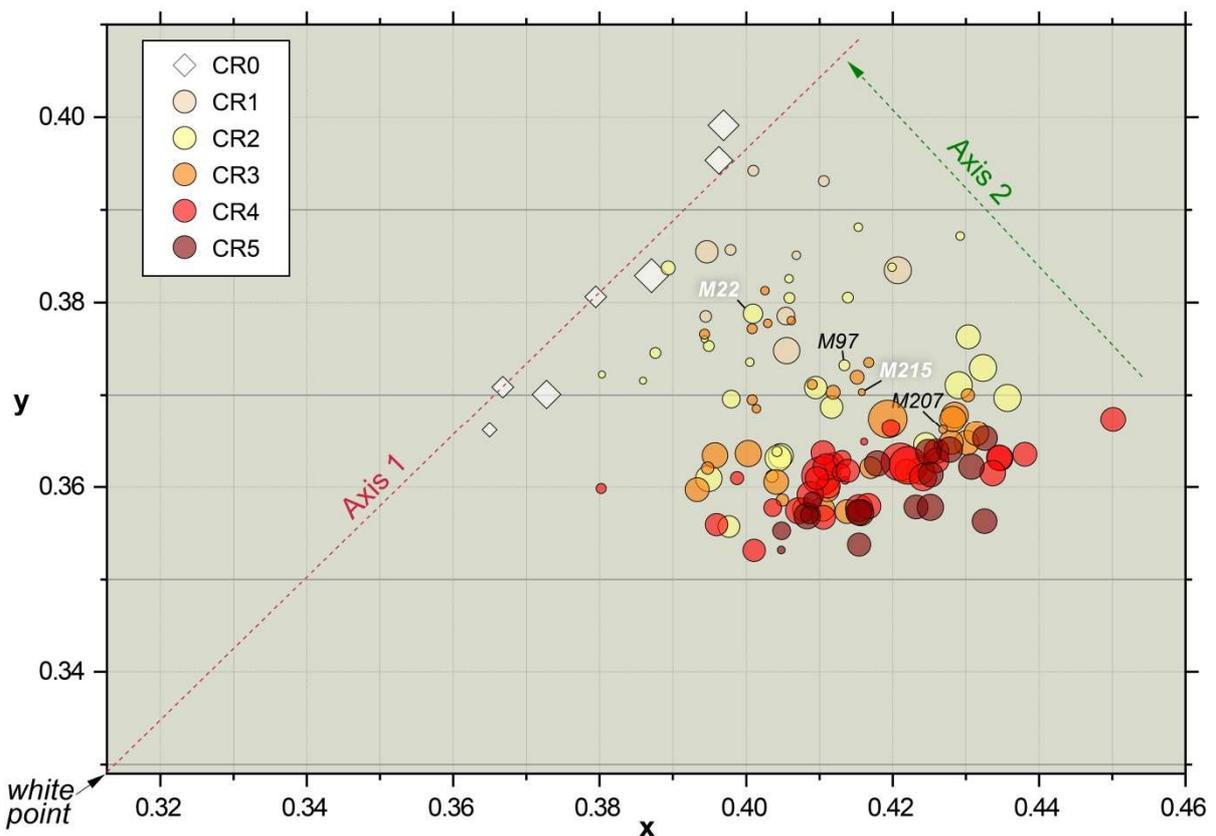
369

At first sight, the distribution of the points on the chromaticity diagram suggests differences in the mineralogical composition of the colouring matter used to make the different types of art. However, detailed examination of the results showed that this distribution is strongly linked to the pigment covering rate, which is indirectly linked to how the colouring matter was applied. The chromaticity values of analysis points with low

370 covering rates (CR1 and CR2) lie in the upper left-hand part of the graph, close to the values  
371 obtained on the undecorated cave walls (CR0). Almost all of these analysis points were on  
372 the line drawings. Apart from a slight difference in luminance, the colorimetry of the  
373 faintest lines is barely distinguishable from the colorimetry of certain parts of the cave wall.  
374 Conversely, the chromaticity values for areas with the highest covering rates (CR4 and 5),  
375 which are mainly solid paintings, are furthest from the values for the undecorated cave wall  
376 (Figure 11). Indeed, chromaticity values vary with pigment covering rate along a gradient  
377 that is approximately perpendicular to the line formed by the bare substrate chromaticity  
378 values (axis 2; Figure 11).

379  
380 A clear shift along axis 2 can be seen for the small number of analysis points we measured  
381 twice but with a different beam diameter for each measurement (obtained by switching  
382 measurement angle without moving the apparatus). In such cases, the wider measurement  
383 area included more of the cave wall surface than the narrower measurement area. This was  
384 particularly the case for measurements M97 and M207, and M22 and M215 (Figure 11).

385



386

387 **Figure 11:** Plot of chromaticity values versus pigment covering rate. CR0: undecorated cave  
388 wall; CR1: < 30%; CR2: 30-50%; CR3: 50-70%; CR4: 70-90%; CR5: > 90%. The size of each dot  
389 is proportional to the diameter of the area measured (in millimetres).

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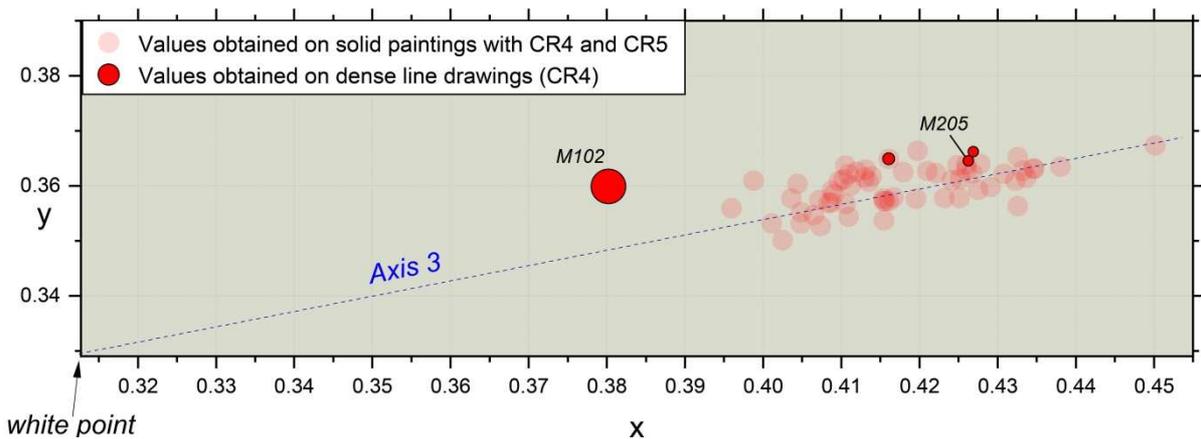
391 These results are consistent with the results of the laboratory experiments, which also  
392 showed a linear relationship between chromaticity values and covering rate (see

393 section 4.2). In both the laboratory experiments and the field measurements, pigment  
394 chromaticity shifted towards the chromaticity values for the bare substrate as the pigment  
395 covering rate decreased (Figure 7). Hence, chromaticity values, whether measured in the  
396 laboratory or in the field, are impacted by two factors independent of the pigment's intrinsic  
397 properties: (a) variations in the colour of the substrate (axis 1) and (b) the pigment covering  
398 rate (axis 2). Logically, when the pigment covering rate is low, the chromaticity for that  
399 measurement point tends to be close to the value for the surrounding undecorated  
400 substrate, hence the spread of values parallel to axis 1.

401

402 This finding raises the question of whether the line drawings were originally the same colour  
403 as the solid paintings. In this regard, values obtained on areas with high covering rates  
404 ( $CR \geq 4$ ) provide better information on the nature of the colouring matter, as the colour of  
405 the substrate has less influence on the resulting chromaticity values of these areas.  
406 Consequently, we focused on line-drawing values obtained at points with covering rates  $\geq 4$   
407 ( $4$  values). These values fit perfectly into the cluster of values for sampling points in the solid  
408 paintings with covering rates  $\geq 4$  (Figure 12).

409



410

411 **Figure 12:** Position on the chromaticity diagram (x,y) of the values obtained at points with  
412 covering rates  $\geq 4$ . The four line-drawings fit perfectly into the cluster of values obtained on  
413 solid paintings. The diameter of the dots is proportional to Y.

414

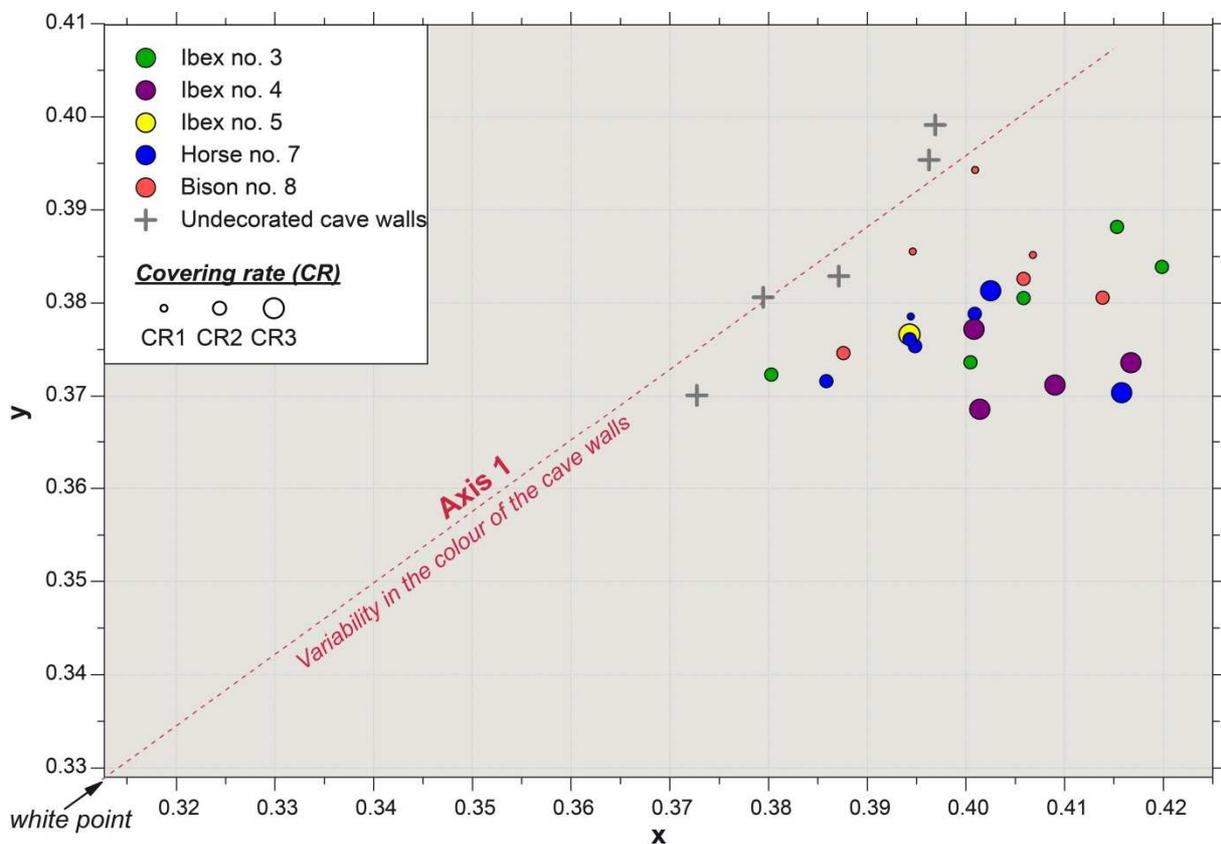
415 Hence, the spread of values along axis 2 is clearly due to a combination of how the pigment  
416 was applied (compared with palm printing and finger tracing, line drawing tends to result in  
417 lower covering rates) and the fact that it is often difficult, or even impossible, to position the  
418 measuring equipment close enough to the cave wall to analyse a line drawing without  
419 including any of the undecorated substrate in the measurement area.

420 In the light of this fact, we reduced the size of the line-drawing analysis points so they  
421 extended as little as possible beyond the pigmented area (Figure 13). Nevertheless, the  
422 analysis points on the drawings were much more likely than those on the solid paintings to  
423 include a sometimes-significant proportion of undecorated substrate. Consequently, the  
424 colour of the cave wall contributed more to the chromaticity values we recorded for the line

425 drawings than to those we recorded for the solid paintings, and the distribution and  
426 clustering of points along axis 2 (Figure 11) cannot be attributed to a fundamental difference  
427 between the colouring matter used for the palm dots and signs and that used for the animal  
428 figures.

429 Because substrate colour is likely to contribute more to the chromaticity values for sample  
430 points with low covering rates ( $CR \leq 3$ ), the contribution of substrate colour may explain the  
431 alignment of the values we obtained in these cases. This factor is likely to have been  
432 particularly prevalent in the case of the animal figures, for which almost all the analysis  
433 points had low covering rates. In fact, the chromaticity values for each animal figure mostly  
434 lie on a line that is more-or-less parallel to the line of cave wall chromaticity values (axis 1),  
435 suggesting that colour variations within each figure are largely the result of variations in the  
436 colour of the cave walls (Figure 13). These considerations show the importance of restricting  
437 comparisons to values obtained in areas with the highest covering rate.

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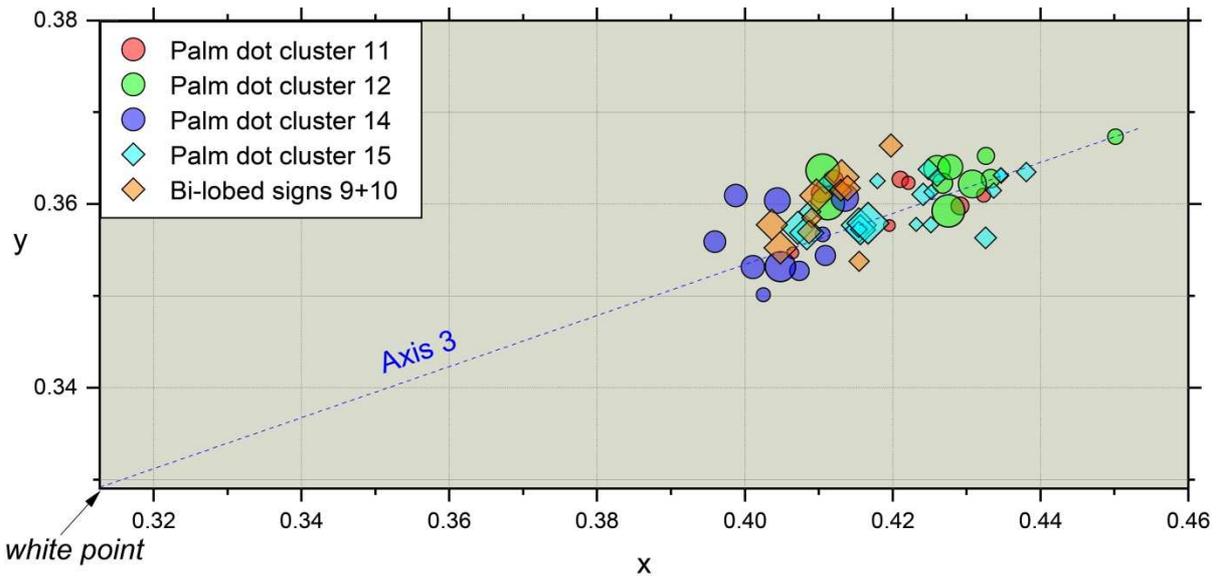
440 **Figure 13:** Plot of chromaticity values for the low covering rate ( $CR \leq 3$ ) analysis points on  
441 the animal figures.

442

#### 443 5.4. Inter- and intra-rock art variability

444 We next addressed the question of whether differences in chromaticity values reflected  
445 intrinsic differences in the colouring matter used for the different types of rock art. To  
446 minimise the impact of other factors, we compared chromaticity values for analysis points  
447 with covering rates  $\geq 4$ .

448



449

450 **Figure 14:** Plot of chromaticity values for analysis points on the solid paintings (palm dots  
451 and bi-lobed signs) with  $CR \geq 4$ . The size of the dots is proportional to Y.

452

453 As for the plot of chromaticity values for analysis points with low covering rates ( $CR_2$  or  
454  $CR_3$ ; Figure 13), the chromaticity values for analysis points with high covering rates lie along  
455 a sub-horizontal line (axis 3; Figure 14), reflecting gradually deeper colours. In addition, the  
456 values form two clusters that are quite distinct, despite a degree of overlap between them.  
457 The chromaticity values obtained on dot cluster 14 and to a slightly lesser extent on bi-lobed  
458 signs 9 and 10 are mostly at the left end of this line, whereas the chromaticity values  
459 obtained on dot clusters 12 and 15 are mostly at the right end of the line (indicating a deeper  
460 colour). Values for dot cluster 11 are centred round the middle of the line and overlap with  
461 the other two groups. This raises the question of whether this grouping of chromaticity  
462 values indicates that the colouring matter used to make the bi-lobed signs and dot  
463 cluster 14 differed from the pigment used to make dot clusters 12 and 15.

464 Although the distribution of colorimetric values along axis 2 can be attributed to analytical  
465 and technical factors (see above), the distribution along axis 3 is more difficult to interpret.  
466 As noted above, considering only the chromaticity values for analysis points with high  
467 covering rates minimizes the influence of the colour of the underlying rock wall. Hence,  
468 variations in the chromaticity values, and the presence of two groups of values, may be due  
469 to a change in the proportions of the colouring matter's components or to differences in the  
470 granulometry and/or morphology of the grains (possibly due to differences in how the  
471 pigment was prepared and/or applied). Another possible explanation is differential  
472 alteration of the colouring matter so that certain components disappear over time. The  
473 alignment along axis 3 may be due to a change in the mineralogical composition of the  
474 colouring matter (see laboratory experiments section above). Given the subtractive nature  
475 of the colouring phenomenon in this case, the colour produced depends on how the  
476 pigment absorbs light. Nevertheless, the alignment of the points along axis 3 is far from

477 perfect, because the colour also depends on the granulometry and microstructure of the  
478 colouring matter.

479 Substantial overlap between colorimetric values obtained on two separate clusters of rock  
480 art would support the hypothesis that both clusters were made using the same colouring  
481 matter. In such cases, outlying values could be due to variations in the wall's roughness and  
482 in the alteration processes that affected each piece of art. However, overlapping values are  
483 not conclusive proof that the same colouring matter was used for both clusters, as each  
484 cluster comprises distinct items. For example, in the case of the clusters of palm dots, the  
485 colouring matter used to make one cluster could also have been used to make a few dots  
486 within another cluster.

487 The fact that chromaticity values for different analysis points on a single dot (or single item  
488 of rock art) fall into different groups is much more significant. This is the case for the  
489 measurements carried out on ibex 4 (values M102 and M205; Figure 12) and on palm dot 15-  
490 02 (M128 and M129). However, M129 was measured in an area bearing a charcoal mark in  
491 addition to the red colouring matter. The presence of this charcoal mark within the analysis  
492 field could be responsible for M129 being lower than the other chromaticity values for this  
493 palm dot and within the range of values obtained on dot cluster 14. However, there are no  
494 reasons to think that either of the values obtained on ibex 4 (M102 and M205) are  
495 problematic.

496 Ultimately, it is difficult to fully explain the differences in chromaticity between analysis  
497 points in areas with high covering rates ( $CR \geq 4$ ). Although we were able to identify groups  
498 of values for pieces/types of rock art and/or locations within Points Cave, with clear overlap  
499 between some of the paintings, we cannot categorically exclude the possibility that these  
500 groupings are the result of environmental and/or taphonomic factors specific to certain  
501 locations in the cave, most notably the presence of thin concretion films that were not  
502 visible in the macro-photographs. Nevertheless, the data currently available strongly  
503 suggest that all the art in Points Cave was made using the same colouring matter or, at  
504 least, colouring matter with a consistent composition. If this is the case, the dispersion in  
505 chromaticity values could be due to colour variability within the deposit of raw materials  
506 used to make the colouring-matter, variations in the way the colouring matter was  
507 prepared, differences in the cave's walls and/or differences in the post-depositional  
508 alteration of each analysis point.

509

##### 510 *5.5. Explaining colour variations in the Points Cave rock art*

511 The chromaticity values obtained on the pieces of rock art varied between the values  
512 obtained on the undecorated cave wall (analysis points with low covering rates) and a deep-  
513 red colour (analysis points with high covering rates). We were able to identify two,  
514 approximately perpendicular alignments within the chromaticity values we recorded. The  
515 first alignment corresponds to changes in the colour of the art as a function of the colour of  
516 the substrate (axis 1: yellowish colours), whereas the second alignment corresponds to the  
517 proportion of an analysis point covered by colouring matter (axis 2: dominance of substrate

518 colour at the top to dominance of pigment colour at the bottom). Our results do not suggest  
519 any other reason for the distribution of the chromaticity values along axis 2 other than the  
520 contribution of the wall colour to the chromatic signal. They do not show that the colouring  
521 matter used for the line-drawn animals is different from that used for the solid paintings.  
522 Conversely, the wall conditions at each analysis point explain quite well the distribution of  
523 the chromaticity values within the graph, with the altered wall surfaces appearing more  
524 yellow. For example, bison 8's yellowish colour is solely due to the very small amount of  
525 colouring matter on the wall at this location.  
526 Further research is needed to explain the distribution of values along axis 3. Current  
527 evidence shows that chromaticity values for a single piece of rock art may vary considerably  
528 along this axis. The most probable reason for this type of variability is differences in  
529 alteration between analysis points. However, we obtained a similar alignment in the  
530 chromaticity values obtained in the laboratory for pigments that differed only in the  
531 proportions of calcium carbonate, kaolin and hematite they contained. Therefore, it is  
532 impossible to rule out the possibility that the distribution of chromaticity values for the  
533 Points Cave rock art is due to differences in the way the prehistoric artists prepared their  
534 pigments and/or to slight colour differences within the deposit from which the colouring-  
535 matter raw materials were extracted.

536

#### 537 **4. Conclusion**

538 The present study provided preliminary answers to our main research questions: Are there  
539 differences in colour between the different pieces of red rock art in Points Cave and, if so,  
540 what are the reasons for these differences? In-situ spectroradiometric analyses of the rock  
541 art revealed slight differences in the chromaticity values for individual pieces of rock art.  
542 These differences can be explained almost entirely by three factors.

543 The distribution of chromaticity values along axis 1 can be ascribed to differences in the  
544 colour of the cave's walls, whereas the distribution of values along axis 2 can be attributed  
545 to differences in the proportions of colouring matter and underlying wall visible within  
546 analysis points. Although we have not yet unequivocally identified the reason for the  
547 distribution of values along axis 3 (sub-horizontal), it is unnecessary to evoke the presence  
548 of different types of colouring matter to explain the data currently available.

549 From an archaeological perspective, our results are consistent with the hypothesis that the  
550 rock art in Points Cave is homogenous in colour and, by extension, that it was made using a  
551 single type of colouring matter. Hence, our results provide additional evidence supporting  
552 the hypothesis drawn from archaeological studies (Monney, 2018b) that all the rock art in  
553 Points Cave belongs to a single prehistoric iconographic project.

554 From a methodological perspective, our study showed the importance of taking into  
555 account the characteristics of the surfaces analysed when interpreting colour  
556 measurements, as it was by doing this that we were able to determine the factor  
557 responsible for the variability along axis 2. Using macro-photographs of each analysis point  
558 to evaluate the pigment covering rate and to identify any other elements in the

559 measurement field (concretions, charcoal marks, etc.) is an essential step in this process.  
560 Consequently, our results highlight the importance of restricting colour comparisons to  
561 areas where the pigment covering rate is greater than 70%.

562

### 563 **Acknowledgements**

564 Funding: This work was supported by the DRAC Occitanie (French Ministry of Culture). We  
565 would like to thank Robin Furestier and Léo Lacheray (FARPA) for managing the funding,  
566 the municipality of Saint-Martin-d'Ardèche (site owner) for allowing us to carry out research  
567 in the cave and the SGGA for authorizing and supervising the use of a power generator. Our  
568 thanks also go to Patricia Guillermin, Philippe Barth, Françoise Prud'Homme and Sonia  
569 Stocchetti (Aven d'Orgnac – Cité de la Préhistoire) for providing accommodation and  
570 technical support. A special thank you to Gwenn Le Saout (Ecole des Mines), Emilie Chalmin  
571 and Emmanuel Malet (EDYTEM laboratory) for providing material resources and technical  
572 support and to Laurent Burgisser, Claire Chanteraud, Chloé Chapignac, Claudia Defrasne,  
573 Aurélien Dumser, Monique Gaultier, Stéphane Jaillet, Arnaud Kherdouche, Robert Loquet,  
574 Guilhem Mauran, Belkacem Otazaghine, Béatrice Racapé, Erik van den Broek, Shirley Sénot  
575 and Didier Ventajol for their invaluable help during portage and fieldwork. We would like to  
576 thank Paul Henderson for his help in proof-reading the English manuscript.

577

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