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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, μ 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.

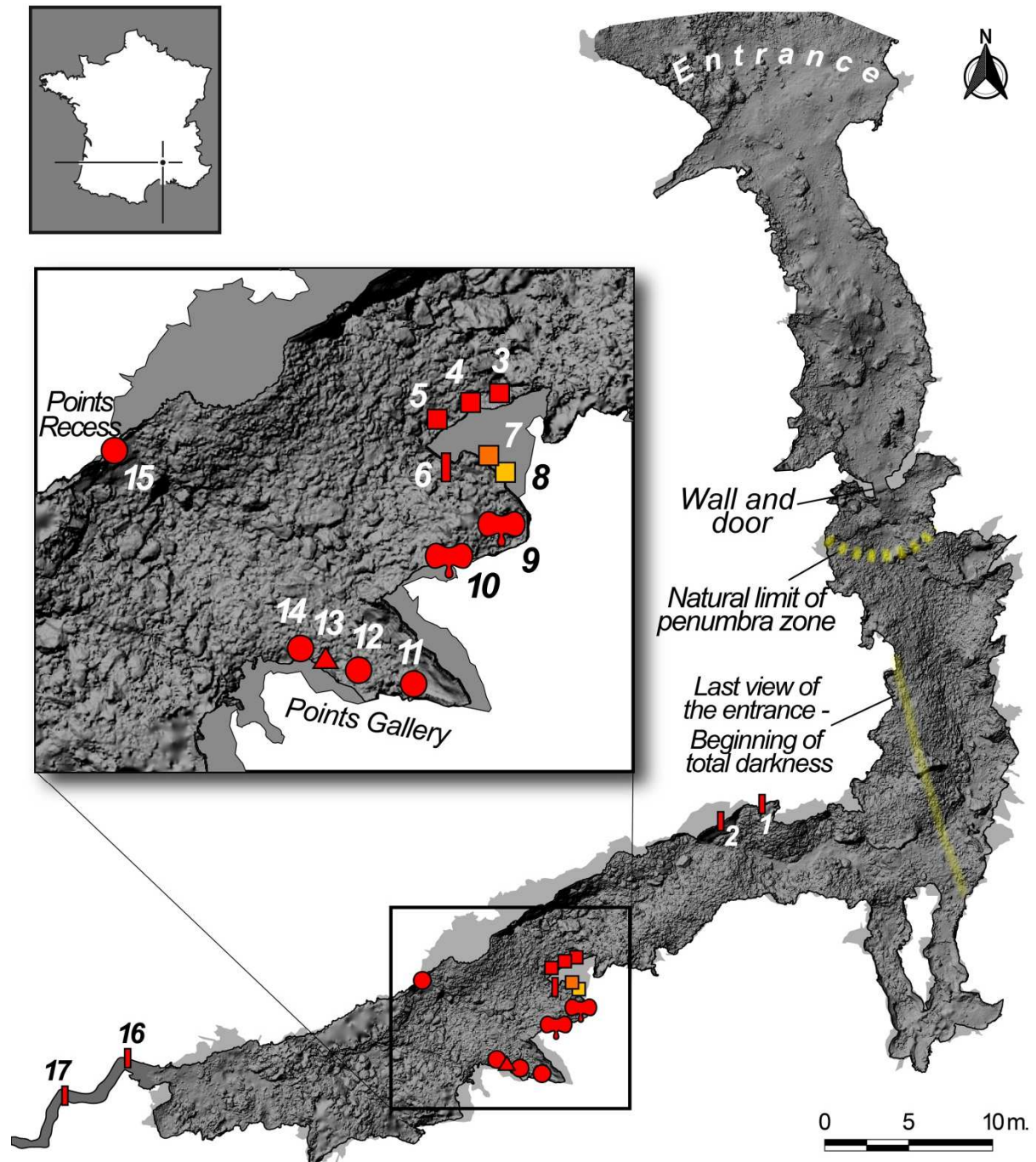
81 With this in mind, and to obtain quantitative measurements we could use to compare the
82 colorimetric properties of different pieces of Palaeolithic rock art within a cave, we carried
83 out an extensive spectroradiometric survey in the visible spectrum (380 to 780 nm) of the

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.

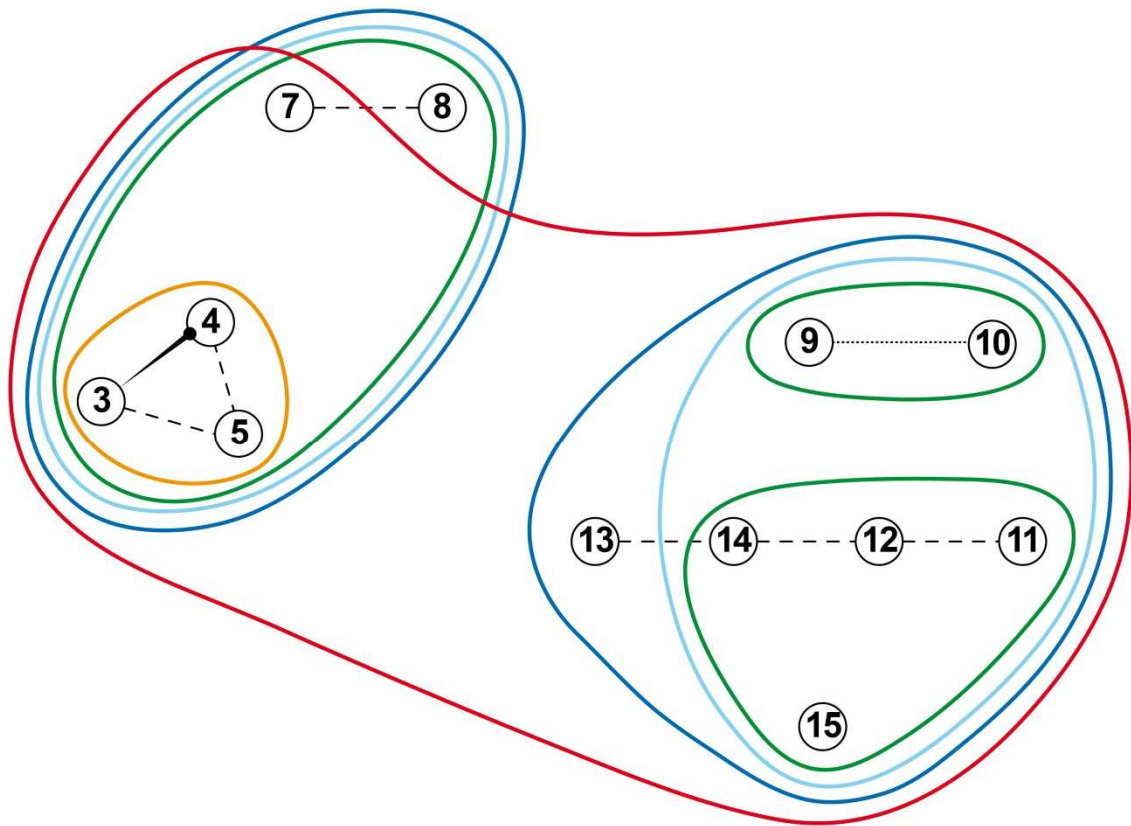


104
105
106
107

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 cd/m^2 for a 1°
151 measurement angle, accuracy of $\pm 2\%$). It also allows the operator to switch measurement
152 angles (1° , 0.2° , or 0.1°) 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° , measurement angle = 0° , 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°) 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° 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

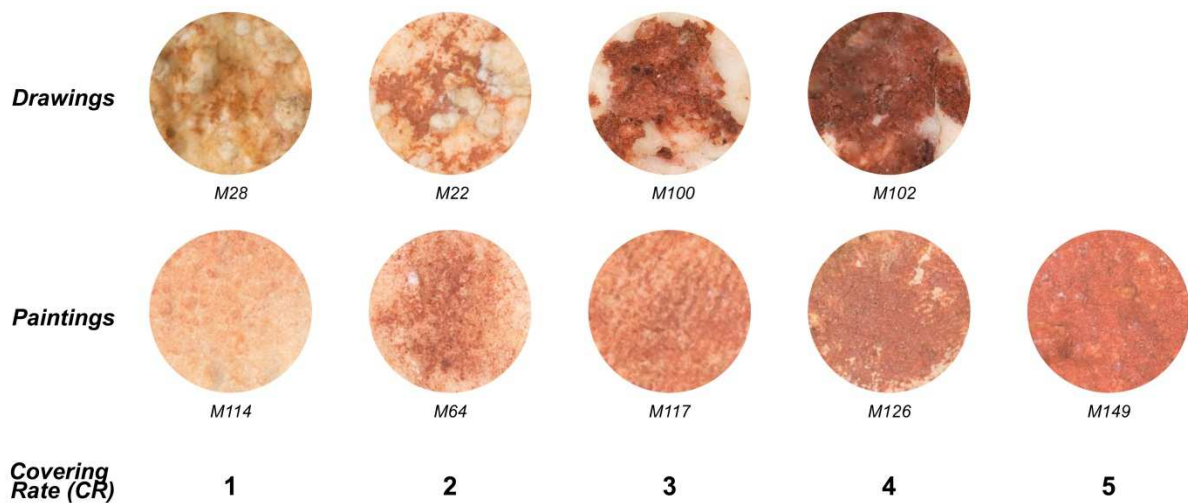
Animal Figures	Type of rock art (technique used)	34
lbex – no. 3	<i>Drawing (pigment applied dry)</i>	5
lbex – no. 4	<i>Drawing (pigment applied dry)</i>	7
lbex – no. 5	<i>Drawing (pigment applied dry)</i>	2
Horse – no. 7	<i>Drawing (pigment applied dry)</i>	8
Bison – no. 8	<i>Drawing (pigment applied dry)</i>	9
V-shaped sign – no. 8bis (on Bison no. 8)	<i>Drawing (pigment applied dry)</i>	3
Bi-lobed signs		13
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
Palm dots		85
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
Open-angle sign		3
Open-angle sign – no.13	<i>Painting (finger tracing)</i>	3
Charcoal marks		2
Charcoal mark – Tch 61		1
Charcoal mark – Tch 82		1
Natural cave walls		7
Total		144

211

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.

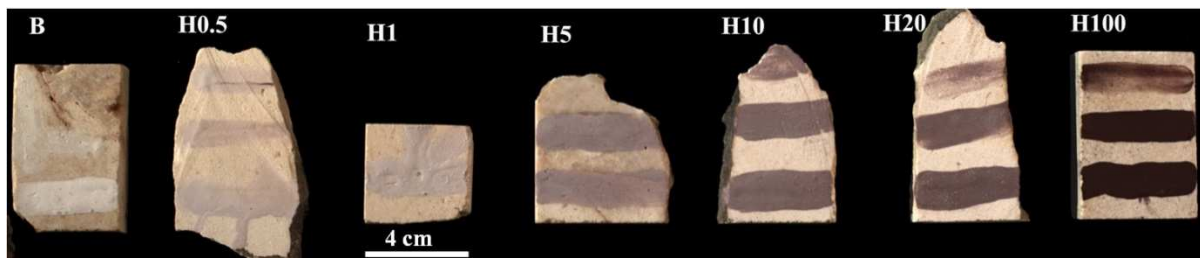
236 As the precise origin of the colouring matter used in Points Cave during the Upper
237 Palaeolithic has not yet been identified (Chanteraud, 2020), we conducted our experiments
238 on mixtures of minerals commonly found in the materials used to make Upper Palaeolithic
239 cave art, that is, kaolin 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

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

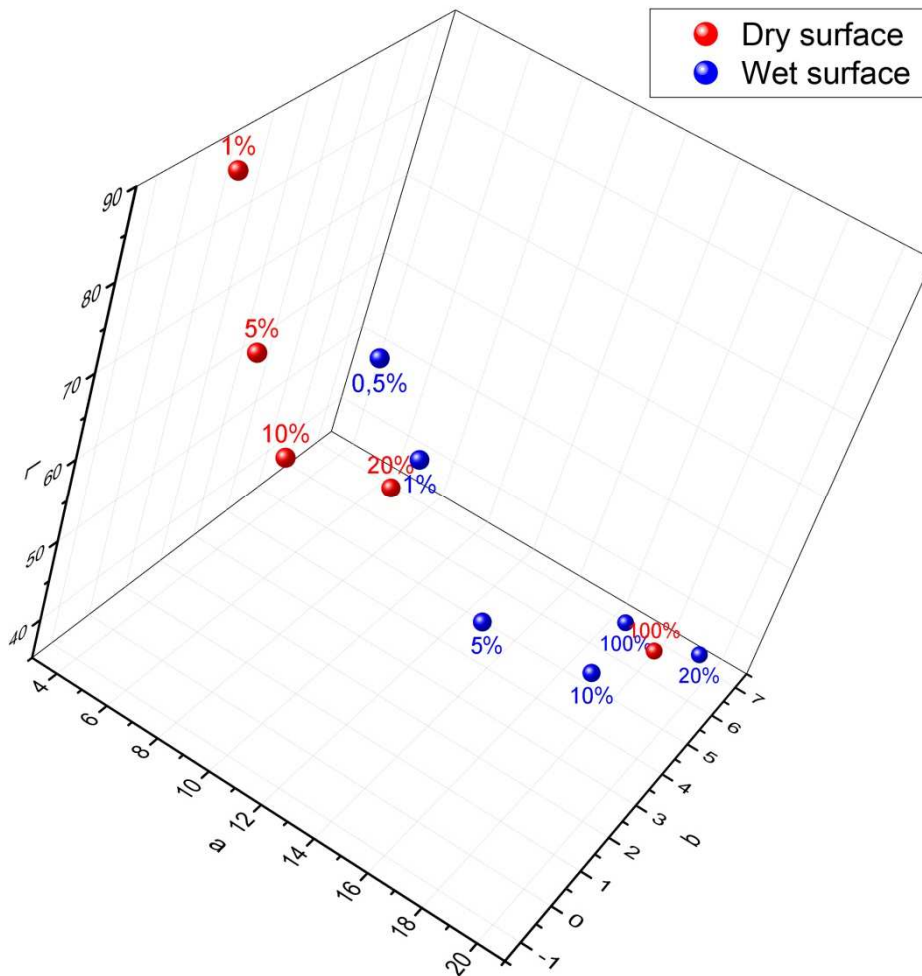
264 *4.1. Field analyses*

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*

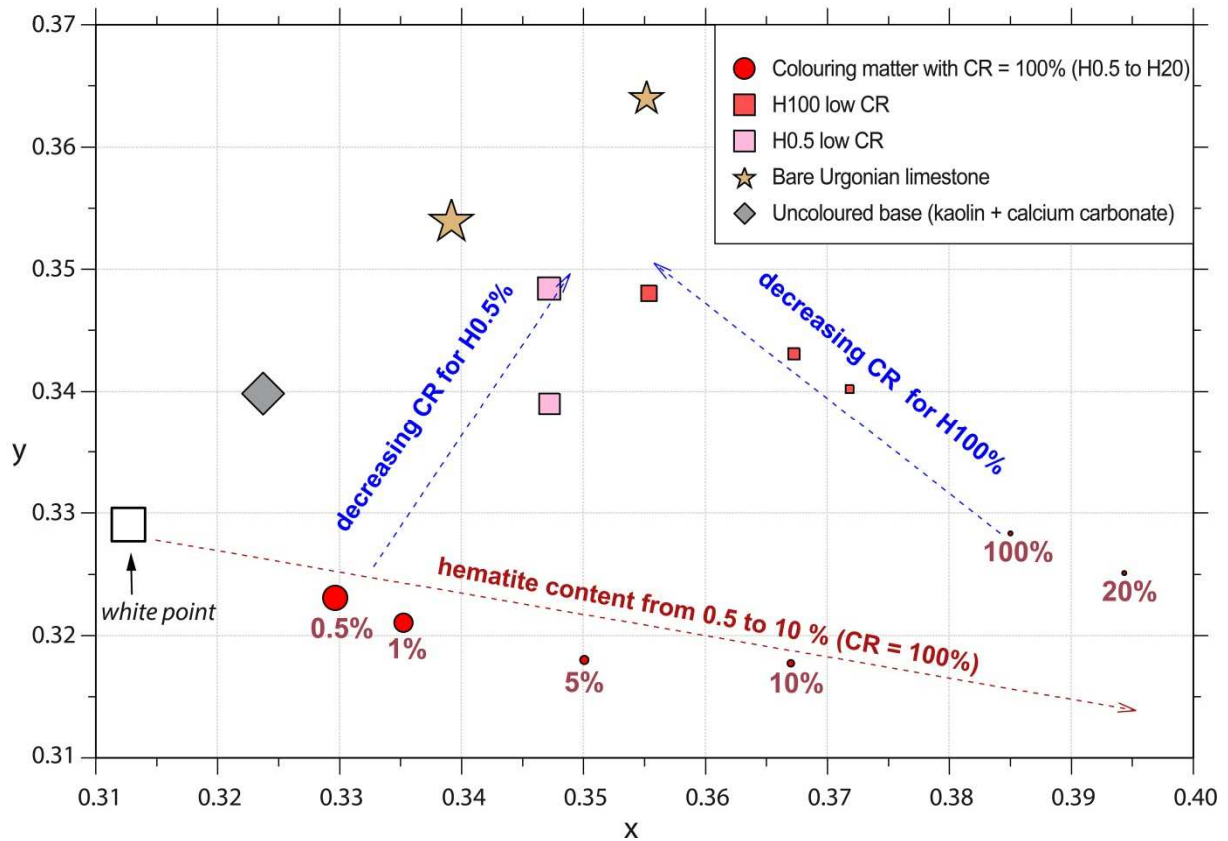
272 We analysed each experimental sample under both wet (limestone block immersed to half
273 height in a water tank) and dry (limestone block air dried for 15 days) conditions. Plotting
274 the values obtained on perfectly covered surfaces in CIELab space (D65; 1931 CIE 2°
275 observer) (Figure 6) showed 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

314

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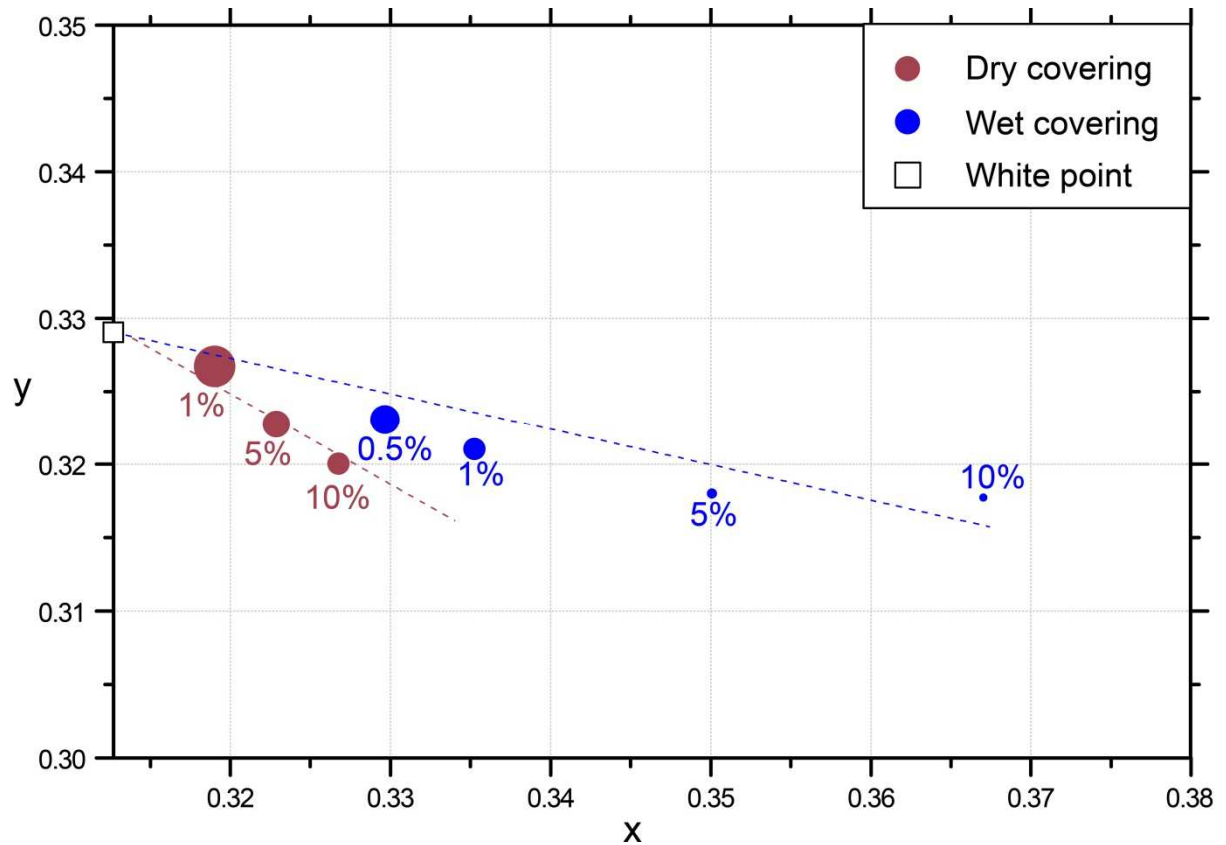
Plotting chromaticity values obtained under wet conditions alongside those obtained under dry conditions clearly illustrates this change in alignment (Figure 8). Differences in colour due to differences in composition appeared more clearly in measurements made under wet conditions.

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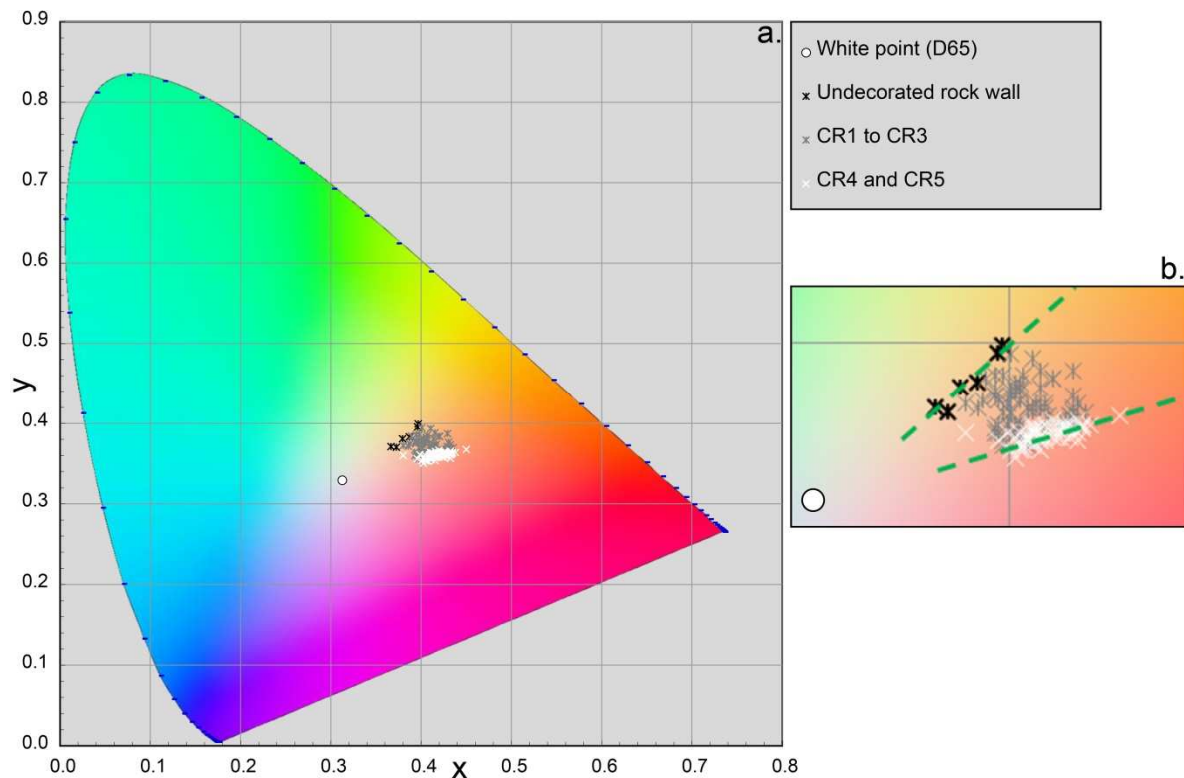
321 **Figure 8:** Plot (1931 CIE 2° observer, D65) of chromaticity coordinates obtained in wet and
 322 dry conditions. The size of the dots is proportional to Y.

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



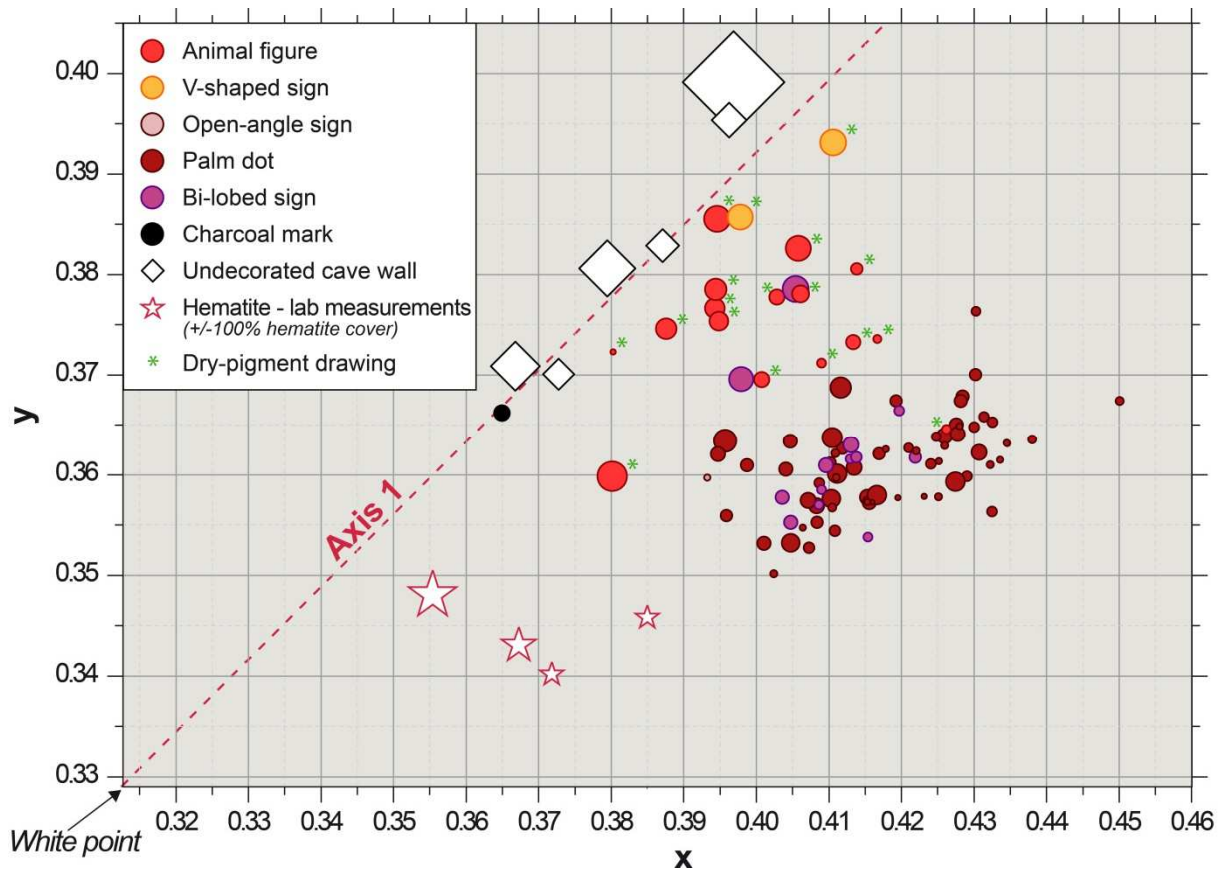
331
 332 **Figure 9:** a: Chromaticity diagram (D65, 1931 CIE 2° observer) showing the values obtained
 333 on the rock art and undecorated walls in Points Cave. Fig. 8b: close-up of the area occupied
 334 by the values. The points are grouped into three classes according to the pigment covering
 335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

346



347
 348 **Figure 10:** Section of the chromaticity diagram showing the position of the measurements
 349 according to the type of surface analysed (rock art or undecorated cave wall). The size of the
 350 dots is proportional to Y.

351
 352 *5.2. Chromaticity coordinates, types of rock art and prehistoric painting techniques*

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

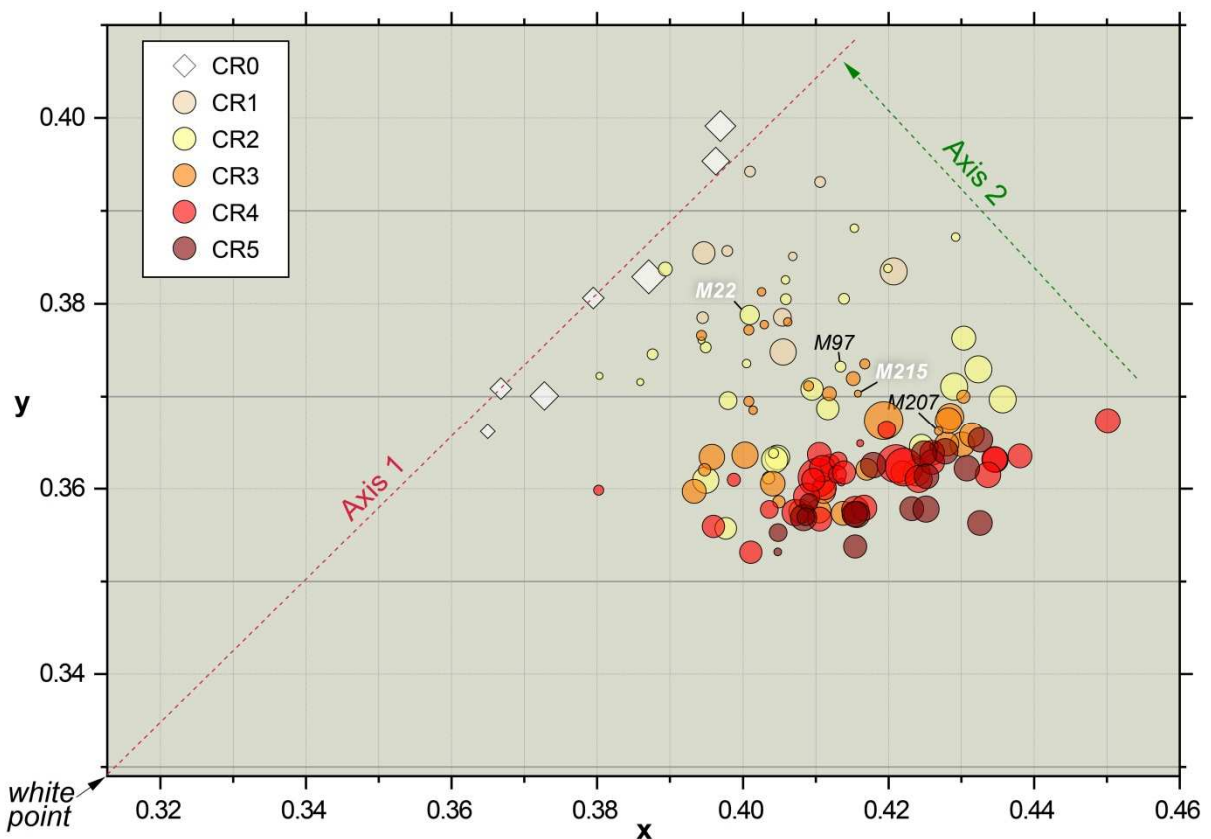
363
 364 *5.3. Relationship between chromaticity coordinates and pigment covering rates*

365 At first sight, the distribution of the points on the chromaticity diagram suggests
 366 differences in the mineralogical composition of the colouring matter used to make the
 367 different types of art. However, detailed examination of the results showed that this
 368 distribution is strongly linked to the pigment covering rate, which is indirectly linked to how
 369 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).

390

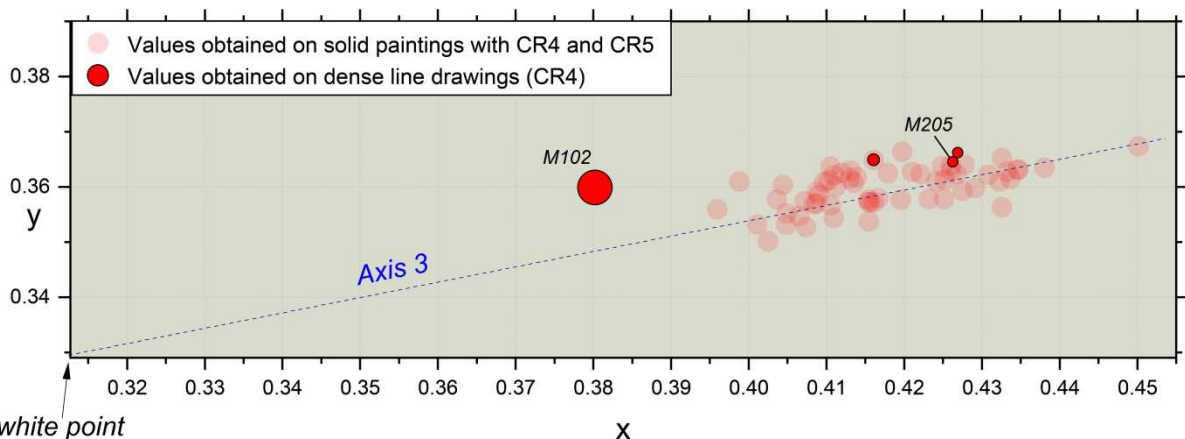
391 These results are consistent with the results of the laboratory experiments, which also
 392 showed a linear relationship between chromaticity values and covering rate (see

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 ≥ 4
407 (4 values). These values fit perfectly into the cluster of values for sampling points in the solid
408 paintings with covering rates ≥ 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 ≥ 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

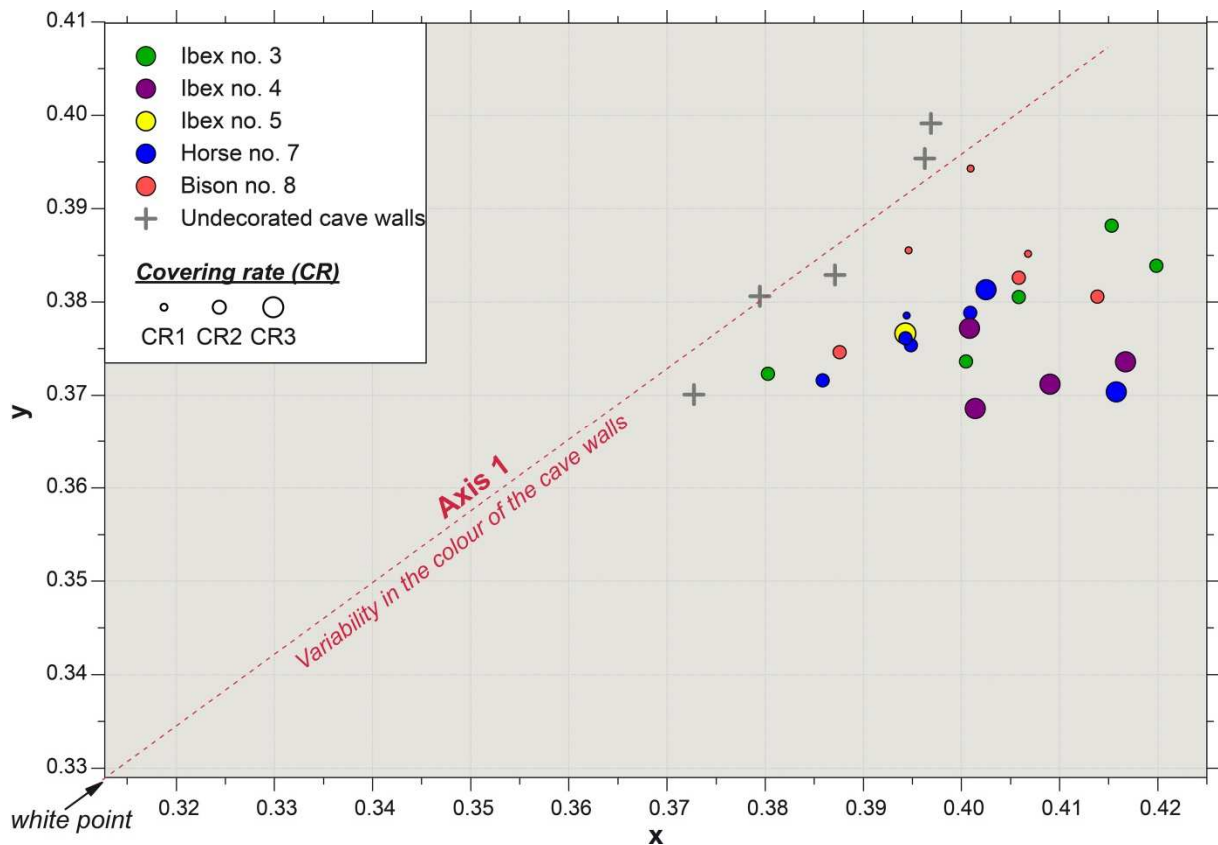
415 Hence, the spread of values along axis 2 is clearly due to a combination of how the pigment
416 was applied (compared with palm printing and finger tracing, line drawing tends to result in
417 lower covering rates) and the fact that it is often difficult, or even impossible, to position the
418 measuring 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.

438



439

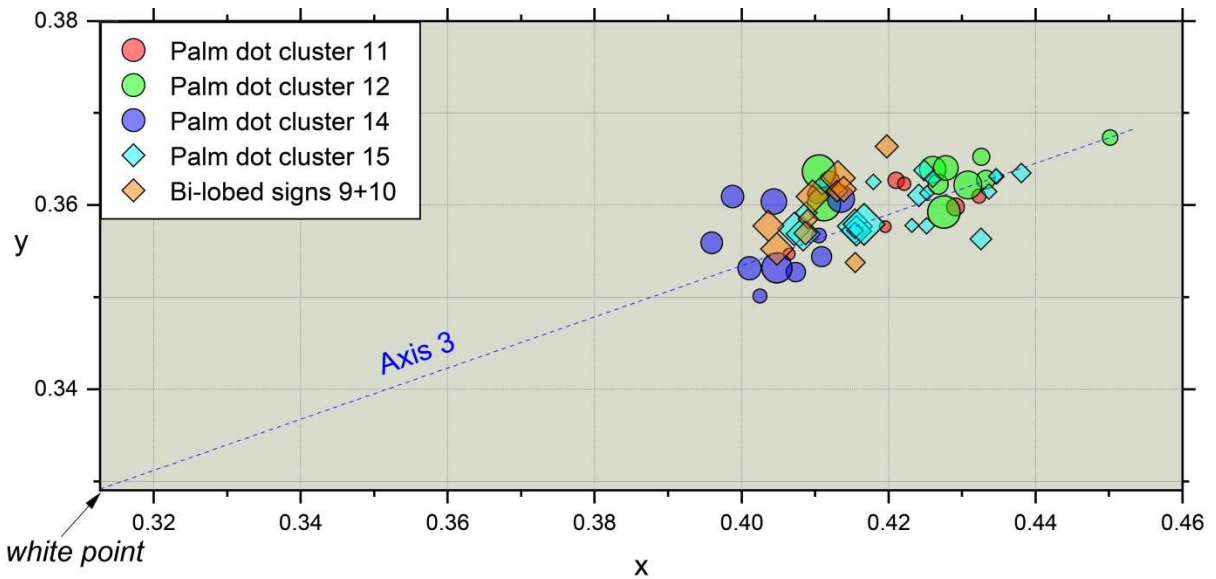
440 **Figure 13:** Plot of chromaticity values for the low covering rate ($CR \leq 3$) analysis points on
441 the animal figures.

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 ≥ 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

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577

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