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Trajectories of cultural innovation from the Middle to Later Stone Age in Eastern Africa: Personal ornaments, bone artifacts, and ocher from Panga ya Saidi, Kenya

Francesco D'errico, Africa Pitarch Martí, Ceri Shipton, Emma Le Vraux, Emmanuel Ndiema, Steven Goldstein, Michael Petraglia, Nicole Boivin

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Abstract

African Middle Stone Age (MSA) populations used pigments, manufactured and wore personal ornaments, made abstract engravings, and produced fully shaped bone tools well before the so-called cognitive shift at 50,000 years ago (ka), formerly considered a key driver in the development of advanced human cultures. However, on-going research across Africa reveals variability in the emergence of cultural innovations in the MSA and their subsequent development through the Later Stone Age (LSA). When present, it appears that cultural innovations manifest regional variability, suggestive of distinct cultural traditions. In eastern Africa, several Late Pleistocene sites have produced evidence for novel activities, but the chronologies of key behavioural innovations remain unclear. The 3 m deep, well-dated, Panga Ya Saidi sequence in eastern Kenya, encompassing 19 layers covering a time span of 78 ka beginning in late MIS 5, is the only known African site recording the interplay between cultural and ecological diversity in a coastal forested environment. Excavations have yielded worked and incised bones, ostrich egg shell beads, marine shell beads, worked and engraved ochre pieces, fragments of coral, and a belemnite fossil. Here we provide a detailed analysis of this material. We demonstrate that behavioural modernity on the eastern African coast is evident by 67 ka, and exhibits remarkable diversity and innovation through the LSA and Iron Age. We suggest the cultural trajectories evident at Panga ya Saidi were shaped by both regional traditions and cultural/demic diffusion.

Keywords	East Africa, symbolism, ornaments, ochre, bone tools, modern human origin
Corresponding Author	Francesco d'Errico
Corresponding Author's Institution	CNRS-University of Bordeaux
Order of Authors	Francesco d'Errico, Africa Pitarch Marti, Ceri Shipton, Emma Le Vraux, Emmanuel Ndiema, Steven Goldstein, Michael Petraglia, Nicole Boivin

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Dear Professor Plavcan

Please find attached the manuscript titled “*Trajectories of Middle to Later Stone Age cultural innovation in eastern Africa: the case of Panga ya Saidi, Kenya*” by Francesco d’Errico, Africa Pitarch Martí, Ceri Shipton, Emma Le Vraux, Emmanuel Ndiema, Steven Goldstein, Michael Petraglia, and Nicole Boivin. We would like you to please consider this manuscript for publication in *Journal of Human Evolution*. Our study aims to document the emergence of key behavioural innovations in the late Middle Stone Age (MSA) and the Later Stone Age (LSA) of eastern Africa.

As you know, a significant debate crosscutting archaeology, paleoanthropology and archaeogenetics has persisted over whether cultural modernity originated and spread uniquely with anatomically modern *Homo sapiens* or whether it emerged in the context of biological and cultural interactions between diverse hominid populations in disparate climatic and geographic settings. Panga ya Saidi, a recently published, well excavated archaeological sequence located north of Mombasa in Kenya, covering the last 78 ka, has yielded a large collection of personal ornaments, bone artefacts, modified ochre and engraved objects spanning the MSA/LSA transition in a continuous sequence that extends into the late Iron Age of recent centuries.

In this paper, we characterize these innovations with the aim of identifying regional trends and similarities with innovations recorded in neighbouring regions, proposing hypotheses regarding the impact of these innovations on late MSA and early LSA eastern African societies, and discussing the implication of this record for our understanding of the emergence of behaviourally modern human cultures.

We suggest the cultural trajectories evident at Panga ya Saidi were shaped by both regional traditions and cultural/demic diffusion.

We think that this article and the rich dataset presented in the Supplementary Materials, consisting of numerous high quality illustrations, will be of interest for a broad scientific audience including paleoanthropologists, Palaeolithic archaeologists, Africanists, researchers in archeometry, and the large public.

We look forward to hearing from you soon.

With kind regards,

Francesco d’Errico

Corresponding author on the behalf of all other authors

Trajectories of Middle to Later Stone Age cultural innovation in eastern Africa: the case of Panga ya Saidi, Kenya

d'Errico, Francesco^{1,2,*}, Pitarch Martí, Africa^{1,3}, Shipton, Ceri⁴, Le Vraux, Emma¹, Ndiema, Emmanuel⁵, Goldstein, Steven⁶, Petraglia, Michael D.^{6,7,8}, Boivin, Nicole^{6,8,9,10}

¹ UMR 5199 CNRS De la Préhistoire à l'Actuel: Culture, Environnement, et Anthropologie (PACEA), Université Bordeaux, Allée Geoffroy Saint Hilaire, CS 50023 F - 33615 Pessac CEDEX, Talence, France.

² Centre for Early Sapiens Behaviour, University of Bergen, Norway.

³ Seminari d'Estudis i Recerques Prehistòriques (SERP), Facultat de Geografia i Història, Departament d'Història i Arqueologia, Universitat de Barcelona, Montalegre 6, 08001, Barcelona (Spain).

⁴ Centre of Excellence for Australian Biodiversity and Heritage, College of Asia and the Pacific, the Australian National University, ACT 0200, Australia

⁵ National Museums of Kenya, Department of Earth Sciences, Box 40658 – 00100, Nairobi, Kenya

⁶ Department of Archaeology, Max Planck Institute for the Science of Human History, Kahlaische Strasse 10, D-07745 Jena, Germany

⁷ Human Origins Program, Smithsonian Institution, Washington, D.C., 20560, USA

⁸ School of Social Science, The University of Queensland, Brisbane, QLD 4072, Australia

⁹ Department of Anthropology and Archaeology, University of Calgary, 2500 University Dr. N.W., Calgary, AB, T2N 1N4, Canada

¹⁰ Department of Anthropology, National Museum of Natural History, Smithsonian Institution, 10th St. & Constitution Ave. NW Washington, D.C. 20560, USA

* **Corresponding Author:** Francesco d'Errico: francesco.derrico@u-bordeaux.fr

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3

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5 **Abstract**

6 African Middle Stone Age (MSA) populations used pigments, manufactured and wore personal
7 ornaments, made abstract engravings, and produced fully shaped bone tools well before the so-called
8 cognitive shift at 50,000 years ago (ka), formerly considered a key driver in the development of
9 advanced human cultures. However, on-going research across Africa reveals variability in the
10 emergence of cultural innovations in the MSA and their subsequent development through the Later
11 Stone Age (LSA). When present, it appears that cultural innovations manifest regional variability,
12 suggestive of distinct cultural traditions. In eastern Africa, several Late Pleistocene sites have produced
13 evidence for novel activities, but the chronologies of key behavioural innovations remain unclear. The
14 3 m deep, well-dated, Panga Ya Saidi sequence in eastern Kenya, encompassing 19 layers covering a
15 time span of 78 ka beginning in late MIS 5, is the only known African site recording the interplay
16 between cultural and ecological diversity in a coastal forested environment. Excavations have yielded
17 worked and incised bones, ostrich egg shell beads, marine shell beads, worked and engraved ochre
18 pieces, fragments of coral, and a belemnite fossil. Here we provide a detailed analysis of this material.
19 We demonstrate that behavioural modernity on the eastern African coast is evident by 67 ka, and
20 exhibits remarkable diversity and innovation through the LSA and Iron Age. We suggest the cultural
21 trajectories evident at Panga ya Saidi were shaped by both regional traditions and cultural/demic
22 diffusion.

23 Introduction

24 The present study aims to document the emergence of key behavioural innovations in the late
25 Middle Stone Age (MSA) and the Later Stone Age (LSA) of eastern Africa. The emergence of
26 innovations such as the use of mineral pigments, the wearing of ornaments and the production of
27 abstract engravings has traditionally been interpreted as the direct consequence of cognitive changes
28 linked to the origin of our species in Africa (McBrearty and Brooks, 2000; Henshilwood and Marean,
29 2003; Shea, 2011; Bruner, 2014; Marean, 2015; Coolidge and Wynn, 2017, Rito et al., 2019). A
30 significant debate crosscutting archaeology, palaeoanthropology and archaeogenetics has persisted
31 over whether cultural modernity originated and spread uniquely with anatomically modern *Homo*
32 *sapiens* (Stringer and Andrews, 1989; Relethford and Harpending, 1994; Klein, 1995; Agani et al., 2011;
33 Henn et al., 2012; see Rito et al., 2019 for an update of this view) or whether it emerged in the context
34 of biological and cultural interactions between diverse hominid populations in disparate climatic and
35 geographic settings (Gunz et al., 2009; Hublin et al., 2017; Neubauer et al., 2018; Scerri et al., 2018).

36 Resolving these issues is critically important for understanding the biological and genomic origins
37 of our species. Unfortunately, the archaeological record for manifestations of hominid symbolism and
38 “modern” innovations remains poorly resolved overall. Current models are shaped by the higher
39 resolution records from Europe (d’Errico and Banks, 2015; Locht et al., 2016; Giaccio et al., 2017; Zilhão
40 et al., 2017) and increasingly southern and northern Africa (Jacobs et al., 2008; Jacobs et al., 2011;
41 Jacobs and Robert 2015; d’Errico et al., 2018). Eastern Africa -one of the assumed centers of human
42 cultural and biological evolution- is represented by only a handful of sites with artifacts indicative of
43 symbolic-mediated behavior and complex bone technology (Ambrose, 1998; Assefa et al., 2008, 2018;
44 Miller and Willoughby, 2014; Rosso et al., 2014, 2016, 2017; Brooks et al., 2018). Most of these have
45 lacked systematic analysis until only very recently (Brooks et al., 2018; Tryon et al., 2018; Miller, 2019).
46 These records are biased toward the Central Rift Valley of the interior, which may not reflect the full
47 diversity of behaviours across the landscape. A greater limitation is that many of these important
48 assemblages lack the chrono-spatial resolution to accurately gauge change over time, are not

49 associated with local climatic data, and/or are not associated with the remains of their hominid
50 creators. As a result, we can assemble a chronology for changes in human symbolism in the region but
51 we lack the data linkages needed to test aforementioned hypotheses regarding the drivers for the
52 emergence of symbolism and symbolic change through time.

53 Panga ya Saidi, a recently published archaeological sequence located north of Mombasa in Kenya,
54 and spanning the last 78 ka (Shipton et al., 2018), has yielded a large collection of personal ornaments,
55 bone artifacts, modified ochre and engraved objects spanning the MSA/LSA transition in a continuous
56 sequence that extends into the late Iron Age of recent centuries. This sequence of symbolic behaviours
57 is well-dated, linked with a high-resolution palaeoecological record and rich technological
58 assemblages (Shipton et al., 2018), and contains human burials that have yielded ancient DNA
59 (Skoglund et al., 2017). Panga ya Saidi is also the only site where systematic flotation and fine mesh
60 screening permitted high rates of recovery for small symbolic artifacts. As a result, the site offers a
61 unique insight into the emergence of key cultural innovations in eastern Africa. We characterize these
62 innovations with the aim of identifying regional trends and similarities with innovations recorded in
63 neighbouring regions, proposing hypotheses regarding the impact of these innovations on late MSA
64 and early LSA eastern African societies, and discussing the implication of this record for our
65 understanding of the emergence of behaviourally modern human cultures.

66 Background

67 The complex and non-linear patterns emerging from our current state of research highlights the
68 need to expand symbolic datasets within Africa. Artifacts that suggest symbolic practices (e.g.,
69 pigments, ornaments, burials, abstract engravings and drawings, systems of notation) appear at
70 different times in Africa and some of them are still not found in vast areas of this continent until a few
71 thousand years ago. Moreover, some of these innovations seem to disappear for thousands of years
72 and then reappear in other forms, contradicting the idea of an exponential expansion of symbolic
73 material culture linked to the sudden origin of new cognitive abilities.

74 The use of mineral pigments is the only innovation that coincides, to a degree, with the beginning
75 of the Middle Stone Age. The recent discovery of modified red ochre fragments at Olorgesailie, Kenya
76 (Brooks et al., 2018) confirms previous discoveries of modified ochre in the early MSA made at
77 Kapturin in Kenya, Twin Rivers in Zambia, and Wonderwerk, Canteen Kopje and Kathu Pan 1 in South
78 Africa (Barham, 2002; Watts et al., 2016). However, considering the age of these findings, 320-280 ka
79 for Olorgesailie and earlier for the southern Africa sites, and what we know about the anatomy of the
80 contemporary African human populations, the first users of ochre pigments probably possessed a
81 number of archaic morphological attributes. Therefore, the first pigment use cannot be taken as
82 reflecting the emergence of modern culture triggered by a speciation event. The first known
83 ornaments, consisting of perforated marine gastropods covered with ochre, belonging to the species
84 *Tritia gibbosula*, are found at sites in Morocco and Algeria dating back to between 120 ka and 80 ka
85 (Bouzougar et al., 2007; d'Errico et al., 2009; Steele et al., 2019). Perforated shells belonging to the
86 same species and bivalves of the genus *Glicymeris*, found at Qafzeh and Skhul, in the Near East, date
87 back to about the same period (Mayer et al., 2009). *Afrolittorina africana* and *Mancinella capensis*
88 shells are used as beads at Sibudu, Kwa-Zulu Natal, in layers dated to between 70 ka and 46 ka (d'Errico
89 et al., 2008; Vanhaeren et al., in press). Perforated and ochred marine gastropods, belonging to the
90 species *Nassarius kraussianus*, are used as ornaments at Blombos Cave, Eastern Cape, around 73 ka
91 (d'Errico et al., 2005). At Border Cave, Kwa-Zulu Natal, a whole *Conus ebraeus* that was perforated and
92 ochred was found in a pit dated to 74 ka, in which the body of an infant was deposited (d'Errico and
93 Backwell, 2016).

94 Abstract representations, engraved on bone and ochre pieces, or drawn with ochre pencils on
95 stone, are found at Blombos Cave, Klasies River, Klein Kliphuis, Sibudu, and Pinnacle Point, South
96 Africa, where they date to between ca. 100-70 ka (Mackay and Welz, 2008; Henshilwood et al., 2009,
97 Watts, 2010; d'Errico et al., 2012). They disappear in the following period and reappear in the same
98 region, but engraved on ostrich egg shells used as flasks for water, ~66-58 ka (Texier et al., 2013;
99 Henshilwood et al., 2014), and later on *Achatina* shells (Bicho et al., 2018) and bone (d'Errico et al.,

100 2012). Abstract representations disappear later and are not found again at African sites until a few
101 thousand years ago. The first African figurative art, discovered in the Apollo 11 cave in Namibia, is only
102 30,000 years old (Wendt, 1975; Rifkin et al., 2015). Although the subject of bitter discussion (Val, 2016;
103 Dirks et al., 2016), the first African mortuary practices could be associated not with modern humans
104 but with a population of *Homo naledi*. Discovered at the bottom of the cave of Rising Star in South
105 Africa, this hominin with a small cranial volume may have survived until between 226 ka and 335 ka
106 (Dirks et al., 2017; Hawks et al., 2017). The very few primary burials discovered on this continent are
107 younger than burials of Neanderthals and modern humans found outside Africa (Pettitt, 2010).

108 What makes it difficult to interpret the first examples of complex technologies and symbolic
109 behaviours from Africa as the direct consequence of a geographically and chronologically constrained
110 emergence of our species is the fact that comparable cultural manifestations are now known in Eurasia
111 before the arrival of modern populations in those regions (e.g., Roebroeks and Villa, 2011; Joordens
112 et al., 2015; Jaubert et al., 2016; Majkic et al., 2017; d'Errico et al., 2018; Hofmann et al., 2018). In
113 other words, the innovations that we encounter at archaeological sites and in which we recognize the
114 first traces of a cognition similar to ours, in particular symbolic manifestations, do not appear to be
115 the direct result of a change related to the sudden emergence of a modern anatomy but rather the
116 expression of complex and apparently non-linear cultural trajectories (Johansson, 2015; Acherman et
117 al., 2016; d'Errico et al., 2017; Colagé and d'Errico, 2018; d'Errico and Colagé 2018; Dediu and
118 Levinson, 2018; Kissel and Fuentes, 2018; Scerri et al., 2018; Will et al., 2019). How these trajectories
119 were, in different regions on the planet, conditioned by biological, environmental, and social factors
120 as well as by migrations and diffusion of cultural traits remains to be explored.

121 The MSA to LSA transition in eastern Africa is marked by the development and proliferation of disk
122 beads, particularly those made from ostrich egg shell (OES). At present, eastern Africa has yielded the
123 earliest occurrences of OES beads, with specimens directly dated to ca. 52,000 BP at Mumba
124 Rockshelter in Tanzania (Gliganic et al., 2012), >50,000 years BP at Magubike Rockshelter in southern
125 Tanzania (Miller and Willoughby 2014), 40,600 BP at Kisese II in central Tanzania (Tryon et al., 2018),

126 and 39,900 BP at Enkapune ya Muto in southern Kenya (Ambrose, 1998). Variation in OES bead
127 representation, size, and morphology through time and space has itself been the source of
128 considerable debate in the Pleistocene through to the Iron Age. While bead sizes seem to generally
129 decrease through the Pleistocene and early Holocene in southern Africa (Miller, 2019), sites in eastern
130 Africa appear to show more heterogeneous patterns. Whereas most sites in the interior appear to
131 show little overall change through time (Miller, 2012; Miller and Willoughby, 2014; Biitner et al., 2017),
132 Tryon et al. (2018) report a slight reduction in disk bead dimensions through the sequence at Kisese
133 II. In southern Africa, a sudden shift to larger bead sizes in the Late Holocene is thought to correspond
134 to the arrival of new populations of herders with different stylistic preferences. So far, there is very
135 little data on any possible shifts in bead size through dynamic population changes now demonstrated
136 through archaeogenetics for the Mid-to-Late Holocene of this region (Skoglund et al., 2017;
137 Prendergast et al., 2019). There are also few indications of periods of intensification of symbolic
138 behaviors that may lend clues to the forces affecting their initial emergence.

139 Bone tools are even less well studied in eastern Africa. The bone tool and notational/ornamental
140 assemblages documented in the MSA of southern Africa (d'Errico and Henshilwood, 2007; Blackwell
141 et al., 2008; d'Errico et al., 2018) and possibly Central Africa (Brooks et al., 1995; Yellen et al., 1995)
142 have no equivalent in eastern Africa. Bone implements first appear *en masse* in eastern Africa in the
143 form of barbed bone points or "harpoons" associated with aquatic resource intensification by foragers
144 during the wet phase of the early Holocene (Yellen, 1998). Similarly, widespread bone ornament
145 traditions are not visible until the Mid-to-Late Holocene (Mehlman, 1989; Helm, 2000; Langley et al.,
146 2017). However, descriptions of five un-serrated bone projectile points, a bone awl, and a bone
147 notched piece from Kuumbi Cave on the Zanzibar archipelago of Tanzania hints at earlier
148 manifestations of osseous technologies on the eastern African coast (Langley et al., 2016).

149 **Material and methods**

150 **Archaeological and paleoecological context**

151 Panga ya Saidi is a large, partially unroofed cave complex located on the Nyali Coast of Kenya, 15
152 km from the present-day shore, at an altitude of 150 m (Figure 1). It opens on the eastern flanks of
153 the Dzitsoni Uplands, a ridge of Middle Jurassic limestone that separates the Late Quaternary coastal
154 plains from the large, arid Nyika Plateau. The site remained in close proximity to the coast throughout
155 the Upper Pleistocene since the sea depth at -125 m is within 5 km of the present shore line.
156 Ecologically, the Dzitsoni Uplands vegetation belongs to the Zanzibar-Inhambane Regional Mosaic. The
157 site is situated at the limit between the Sokoke Forest, characterised by the association *Cynometra-*
158 *Manilkara* and the Shale Savanna with *Manilkara-Dalbergia*. Climate models (Shipton et al., 2018)
159 suggest that during the Last Interglacial the Nyika Plateau received less rainfall than the present
160 interglacial, while the coastal area where the site is located witnessed higher precipitation in the Last
161 Glacial Maximum than at present.

162 Excavations conducted at Panga ya Saidi between 2010 and 2013 have reached a depth of 3 m
163 (Shipton et al., 2018). The sequence includes, from the bottom to the top, four lithological units (Units
164 I-IV) encompassing 19 archaeological layers (Figure 2). Although animal burrows, tree root channels
165 and termite galleries were recorded during the excavations, most stratigraphic boundaries could be
166 identified along the entire profile. Twelve stratigraphically coherent AMS radiocarbon and seven OSL
167 ages indicate that the sequence accumulated between MIS 5 (~ 78 ka) and the historical era (0.4 ka).
168 Unit I (Layers 19-17), featuring a relatively low occupation density, is followed, at the Unit I/II interface
169 (Layer 17/16) by a possible depositional hiatus and limited human use of at least the part of the cave
170 sampled. Anthropogenic signatures, in the form of ash and burnt bone, gradually increase within Unit
171 II (Layers 16 to 14). This trend is interrupted by a sharp surface of erosional relief separating the top
172 of this unit from the archaeologically richer Unit III (Layers 13 to 5). This unit comprises numerous ash
173 lenses interpreted as burning features. Stratigraphic interfaces interpreted as occupation surfaces

174 with some degree of erosion are identified within Unit III, in particular at the Layer 13/12 and Layer
175 10/9 boundaries. The overall sequence is as follows: Layers 1-3 (Iron Age), Layer 4 (earlier Holocene),
176 Layers 5-6 (terminal Pleistocene), Layers 7-8 (Last Glacial Maximum), Layer 9 (late MIS 3), Layer 10
177 (mid-MIS 3), Layers 11-12 (early MIS 3), Layers 13-16 (MIS 4), and Layers 17-19 (late MIS 5). A range
178 of palaeoecological indicators identify a persistence of more or less open tropical forest throughout
179 the sequence. Within this general trend, several proxies suggest slightly drier conditions during the
180 deposition of Layers 16 (71-67 ka) to 8 (20 ka).

181 A significant increase in archaeological finds and a change in stone artifact size, technology, raw
182 material and tool type are recorded after the Unit I - II transition (73-67 ka). Lithic assemblages from
183 Unit I are primarily composed of typical MSA large flakes, mostly made of limestone, produced with
184 the Levallois method, occasionally retouched into points. The shift to a largely predominant use of
185 quartz (70-90%) in Units II and III corresponds to an increased use of bipolar technology and a
186 reduction in stone tool size. Chert use increases (40-60%) in Unit IV. Backed crescents appear for the
187 first time in Layers 11 and 12 (48.5 ka) and are also found from Layer 6 upwards. They co-exist in Units
188 II and IV with bipolar and Levallois technology, with blades becoming common in the upper part of
189 the sequence (Layers 8-3; 25-1 ka). The increase in archaeological remains observed in Units II-IV is
190 tentatively interpreted by Shipton and colleagues (2018) as evidence for a growing human presence
191 in the region, while the absence of unidirectional changes in lithic technology is seen as an indication
192 that this region did not witness the sudden appearance of an LSA technological package.

193 **Methods**

194 Over 200 potential beads, bone tools, engraved bone and stone objects, and pigment lumps
195 recovered during excavations were examined under a low power reflected light microscope to assess
196 potential anthropogenic modifications. When necessary, sediment was carefully removed under the
197 microscope with a soft brush or a wet toothpick. This resulted in the retention of 180 pieces bearing
198 compelling traces of manufacture and use, unmodified or marginally modified shell fragments

199 probably used as beads, and modified and unmodified lumps of iron-rich rocks and sediments, possibly
200 used to produce ochre powder.

201 The identification of the most probable ostrich sub-species that laid the eggs used to produce the
202 circular beads found at Panga ya Saidi was based on guidelines proposed by Schönwetter (1927), Sauer
203 (1972), Mourer-Chauviré and Geraads (2008), and Blinkhorn et al. (2014). Taphonomic analysis of
204 *Conus* shells was based on Harding (1961), Mattes (1974), Claassen (1998), and d'Errico and Backwell
205 (2016). The identification of traces of manufacture, heating and use-wear on beads made from marine
206 shells and OES relied on diagnostic criteria established experimentally (d'Errico et al., 1993; d'Errico
207 et al., 2005; d'Errico et al., 2009), as well as previous analyses of similar objects (Kandel and Conard,
208 2005; Orton, 2008; d'Errico et al., 2012; Wei et al., 2017).

209 The distinction between natural and anthropogenic modifications on worked bone was based on
210 criteria defined in the literature and on the analysis of modern and Pleistocene reference collections
211 (Binford, 1981; Bonnichsen and Sorg, 1989; Villa and d'Errico, 2001; Backwell and d'Errico, 2001,
212 2005). Identification of shaping techniques and use-wear was based on data from experimental bone
213 tool manufacture and use (Newcomer, 1974; d'Errico et al., 1984; Bergman, 1987; Shipman and Rose,
214 1988; Choyke and Bartosiewicz, 2001; Backwell and d'Errico, 2005), and experimental reproduction
215 and microscopic analysis of marks produced with different tools and motions (d'Errico, 1995, 1998).

216 The identification of grinding, scraping and traces of deliberate engraving on ochre fragments is
217 based on criteria obtained from experimental research (d'Errico and Nowell, 2000; Soressi and
218 d'Errico, 2007; Hodgskiss 2010; Rifkin, 2012; Rosso et al., 2017), examinations of engravings on stone
219 and bone surfaces (d'Errico, 1995, 1996), and by comparison with published engraved pieces from
220 Blombos Cave and Klasies River (Henshilwood et al., 2002, 2009; d'Errico et al., 2012).

221 Two to four sides of each artifact were digitised at a resolution of 2400 dpi with an Epson Perfection
222 V600 Photo scanner. Artifacts were examined at magnifications between 4x and 40x, and
223 photographed with a motorised Leica Z6 APOA microscope equipped with a DFC420 digital camera.
224 Uploaded images were treated with Leica Application Suite (LAS) equipped with the Multifocus

225 module, and Leica Map DCM 3D computer software. Selected areas of one *Conus* were scanned using
226 a Sensofar Sneox scanning confocal microscope using a 20x objective. The resulting files were analysed
227 with Mountains 7.2 software.

228 Different variables were recorded for each artifact category. Morphometric data were collected on
229 all objects with digital callipers. On shaped beads, we recorded raw material, bead shape, colour,
230 traces of manufacture, perforation technique, traces of heating, morphology of the perforation (sub-
231 conical, biconical, cylindrical and sub-cylindrical), the hole (circular, sub-circular, ovoid), and the hole
232 aperture at the level of the bead surface, presence of pigment residues, and thickness and maximum
233 and minimum diameter of the bead, the hole and the aperture. Identification of OES bead types,
234 corresponding to different size, technology and style of manufacture, has taken advantage of
235 discussions with Gwaxan Cgonta, an OES beads maker and member of the Ju/'hoansi community,
236 Nyae Nyae, near Tsumkwe, Namibia, as well as analysis of OES beads from Shuidonggou locality 2 (Wei
237 et al., 2017). On anthropogenic perforated marine gastropods, we recorded species, shell length,
238 width, maximum and minimum diameter of the perforation, perforation technique, and traces of
239 shaping and use-wear. On naturally perforated or slightly modified spiral fragments of *Conus*, we
240 recorded, if any, location and type of modification, maximum width and thickness of the fragment,
241 and perforation maximum diameter. The raw material from which four shaped beads, tentatively
242 identified in the field as made of "shale" or "slate", was manufactured, was assessed by optical
243 microscopy and micro-Raman spectrometry (μ -RS). We used for this purpose a SENTERRA Dispersive
244 Raman Microscope (Bruker), equipped with an internal calibration system. Spectra acquisitions were
245 done with a 532 nm laser, a laser power of 2 mW, an integration time of 60 s, and multiple co-
246 additions. The working area was observed through the integrated colour camera, and data was
247 collected with the software package OPUS 7.2. Identification of mineral phases was based on the
248 comparison of the recorded spectra with those of the RRUFF spectra library (Lafuente et al., 2015).

249 The following parameters were recorded, wherever possible, on worked bone and teeth:
250 anatomical and species origin of the blank, mammal size class, blank extraction and shaping technique,

251 traces of use, sharpening, and the length, width and thickness of the object. The location and extent
252 of worked areas and the sequence of the technical actions, based on microscopic examination, were
253 systematically recorded for each artifact.

254 Variables recorded on iron-rich lumps included type and location of anthropogenic modification,
255 colour, and texture. The elemental composition of two modified iron-rich lumps was established by
256 energy dispersive X-ray fluorescence (EDXRF) and analysis using a scanning electron microscope
257 coupled to an energy dispersive spectrometer (SEM-EDS). The former was not used on unmodified
258 lumps because of their small size. EDXRF measurements were performed with a portable SPECTRO
259 xSORT X-ray fluorescence spectrometer from Ametek, equipped with a silicon drift detector (SDD), a
260 low power W X-ray tube with an excitation source of 40 kV, and an X-ray beam of 8 mm. Spectra
261 acquisition times were set to 300 s. The spectrometer is internally calibrated by an automated
262 measure of the elemental composition of a standard metal shutter. Measurements were acquired
263 using a positioning device consisting of a lead receptacle to which the spectrometer was fixed. Three
264 measurements per object were obtained. SEM-EDS analyses were performed using a FEI Quanta 200
265 with SiLi detector, and SDD-EDAX detector. Backscattered electron images (BSE) and elemental
266 analyses were obtained under a low vacuum mode with an accelerating voltage of 15 kV. The EDS
267 analyses were performed under similar magnifications at the same working distance (10 mm), and
268 with the same acquisition time (100 s) for each EDS spectrum. The mineralogical composition of
269 modified and unmodified iron-rich lumps was determined by Raman spectroscopy using the same
270 equipment employed on shaped beads. For these last samples, the measurements were done with a
271 785 nm laser and a power of 1 mW in order to avoid thermal transformation of mineral phases. The
272 spectra were recorded with an integration time varying from 5 to 10 s, in a spectral range from 100 to
273 2200 cm^{-1} , and with a number of co-additions varying between 15 to 25 depending on the presence
274 of fluorescence radiation and signal-to-noise ratio.

275 **Results**

276 **Personal ornaments**

277 Five main personal ornament categories were recorded at Panga ya Saidi: perforated *Conus*
278 spires, OES beads, perforated marine gastropods, circular shell beads and tubular shell beads
279 (Figures 3-10). We present here a description of these artifacts and provide information on their
280 technological, morphological and dimensional variability. Results concerning these artifacts are
281 summarised in Tables 1-2.

282 *Perforated Conus sp. spires*

283 These objects are fragments of *Conus* shells resulting from the natural degradation of the thick
284 shells and robust spires belonging to this genus (Table 1). Destruction of these shells begins with the
285 gradual fading of the pattern, and continues with the fracture of the outer lip, bioerosion, opening of
286 perforations on the body whorl, progressive reduction of the latter by fracture and/or erosion until
287 only the spire, or fragments of the remainder of the shell survive (Figure S1). Degradation proceeds
288 with the gradual erosion of the spire, leading to the eventual opening of a hole at the apex (Claassen,
289 1998; d'Errico and Backwell, 2016). When occurring on *Conus* shells with flat spires the perforation
290 may give the impression that the spire was flattened by abrasion to open a hole at the apex. *Conus*
291 fragments at this final stage of destruction, consisting of polished dome-shaped disks with a
292 perforation in the middle, commonly known as “puka shells”, are intensively used for jewellery in
293 Hawaii (Mattes, 1974). Similar uses are attested in Africa (Harding, 1961). The size of the perforations
294 in puka shells increases proportionally as the fragments reduce in size. This explains why the
295 perforations on *Conus* fragments recovered at Panga ya Saidi display, comparatively to other bead
296 types, a wide range of variation. The distance of Panga ya Saidi from the coast and identification of
297 two cases in which the natural perforations were marginally modified favour an interpretation of these
298 shell fragments as beads. Apart from two specimens found in Layers 16 and 10, this bead type is
299 concentrated in Layers 8 and 9, where 17 of the beads were recovered. The two specimens that show

300 possible evidence of modification come from Layers 16 and 8. The first exhibits traces of grinding
301 followed by polishing of the spire in an area close to the perforation (Figure S2, A). The second shows
302 on the perforation edge a small well-preserved area covered with striations possibly indicating that
303 the hole was slightly enlarged by rotation (Figure S2, B).

304

305 *Ostrich egg shell beads*

306 Eighty-eight OES beads were recovered at Panga ya Saidi. A single specimen comes from Layer
307 9. The large majority of the others come from Layers 7-8, only a dozen from Layers 5-6, and five
308 from Layers 2-4. Breathing pores detected on well preserved areas of the egg outer surface are
309 concentrated in clusters of individual pores or alignments of pores (Figure S3). This feature indicates
310 that *Struthio camelus massaicus* and/or *Struthio camelus molybdophanes* are the more likely sub-
311 species that have produced the eggs employed to make the beads (Schönwetter, 1927, Sauer,
312 1972). This attribution is consistent with the present geographical distribution of these sub-species.
313 *S. camelus massaicus* is common in Kenya and southern Somalia, *S. camelus molybdophanes* in
314 Ethiopia and northern Somalia. The two subspecies are sympatric in a large north-west to south-
315 east oriented band covering the north of Kenya and the south of Somalia, which may have shifted
316 during the Upper Pleistocene in response to climatic changes. Although variably modified by
317 abrasion and polishing, the egg thickness measured on the beads (mean of 1.77 mm with a range
318 between 1.32 mm and 2.16 mm) is consistent with these attributions.

319 Morphological and technological analyses (Figure S4) reveal notable differences in OES beads
320 manufacture and style within and between layers. Six main types are identified (Figure 9): Type A
321 includes large circular OES beads with large perforations. They exhibit polished to highly polished
322 faces, elliptical and often slightly off-centred perforations, and straight or slightly convex edges in
323 cross section. The edge formed by the intersection of the egg shell's original surface with the
324 perforation is very regular on the inner shell surface (interior perforation edge), but very irregular
325 on the outer surface (exterior perforation edge). This indicates that the perforation was made from

326 the inner toward the outer surface of the egg shell (Wei et al., 2017). Type B includes very large
327 circular OES beads with relatively small perforations. These beads exhibit slightly polished faces,
328 circular perfectly centred perforations, and slightly convex edges in cross-section. Interior and
329 exterior perforation edges are both slightly irregular. Type C includes small polygonal OES beads with
330 small polygonal perforations. These beads exhibit scars left by trimming the edge of the bead
331 preform, smoothed by polish, very convex edges in cross section, bi-conical perforations with very
332 flared edges and very irregular interior and exterior perforation edges. Type D includes sub-
333 circular/ovoid OES beads with circular perforations. These beads exhibit polished to highly polished
334 surfaces, slightly irregular interior and exterior perforation edges, and variable edge shape along
335 their cross sections. Type E includes small circular OES beads with comparatively large circular
336 perforations, diffused interior and exterior perforation edges, and convex cross-sections all over the
337 bead surface. Type F includes very small OES beads with very small perforations. These beads exhibit
338 highly polished faces, circular perfectly centred perforations, perfectly straight edges in cross
339 section, and cylindrical perforations with very regular interior and exterior perforation edges. Eight
340 OES beads do not fall into these categories. Each of them exhibits a distinct combination of
341 dimensional and technological features (Figure S5). One is sub-circular in shape and bears a very
342 small perforation with flared edges (Figure 5, n. 33; Figure S5, A). A second has a general morphology
343 reminiscent of type B while being smaller in size and displaying flared perforation edges (Figure 5,
344 n. 35; Figure S5, B). A third is also reminiscent of type B but differs from the OES beads attributed
345 to this type by its smaller size, irregular outline and bi-conical perforation with flared edges (Figure
346 5, n. 53; Figure S5, C). A fourth associates the perforation size and general appearance of type A OES
347 beads with a polygonal outline (Figure 5, n. 57; Figure S5, D). A fifth consists of a small OES beads
348 with a polygonal outline, a small perforation with flared edges on the inner side of the egg, and a
349 polish reminiscent of type A (Figure 4, n. 7; Figure S5, E). A sixth differs from the previous one in
350 that it exhibits a circular outline and is characterised by an even more flared perforation edge on
351 the inner side of the egg (Figure 4, n. 8; Figure S5, F). A seventh associates an irregular sub-circular

352 outline with a small perforation and a very convex edge in cross section (Figure 3, n. 16; Figure S5,
353 G). The eighth is larger than type F, but smaller than the other beads, and differs from the OESBs
354 attributed to type F in the bi-conical shape of the perforation (Figure 3, n. 48; Figure S5, H).

355 Apart from two specimens, found in Layer 5, Type A is concentrated in Layers 7-8. Types B is also
356 concentrated in Layers 7-8 with two specimens of this type found in Layers 6 and one, the
357 lowermost OESB recovered at the site, in Layer 9. Six of the seven specimens of Type C are also
358 found in Layers 7-8, the seventh coming from Layer 5. Type D and E are only present in Layers 5-6
359 and Type F in Layers 2 and 3.

360 Thirty-three OES beads (37%) bear evidence of having been heated to darken them. This
361 treatment is, in fourteen cases, responsible for the splitting of the bead (Figure 5). Only OES beads
362 belonging to Types A, B, and D were submitted to this treatment, which was not used for the small
363 irregular beads of Type C and E, nor for the three small OES beads found in Layer 2 and 3.
364 Interestingly, heating was applied to morphologically and dimensionally similar beads made of
365 marine shells, found in the same layers (see below). Four of the eight beads falling outside the main
366 OES bead types have also been heated (Figure S6). Differences in shade suggest that the technique
367 was not equally mastered. Type A OESBs exhibit, when heated, a very dark black shade, which is
368 also found in those attributed to Type D and one of the unclassified OESBs (Figures S4 and S5). This
369 black shade is only rarely observed with Type B OESBs. Around 70% of OESBs, from all layers, bear
370 residues of possible pigment on the perforation and faces, less frequently on the edge (Figure S7).
371 All beads exhibit traces of utilization suggesting that they have been lost or disposed of after being
372 used as personal ornaments (Figure S4).

373 Morphometric analysis of OESBs confirms to a great extent the grouping based on visual
374 discrimination. The scatterplot correlating bead and perforation maximum diameters (Figure 10)
375 shows that Types A and B cluster separately and are characterised by mutually exclusively bead and
376 perforation sizes. This suggests that the grooved stones used to produce them and drilling tools that
377 have perforated them were different. Type C beads are smaller than Type B and their perforations

378 fall outside Type A and F variation. They represent the only type of beads having a wide range in
379 diameter and a high degree of correlation between diameter of the hole and the bead. Due to their
380 irregular morphology and size, as well as their poor manufacture quality, the artisan/s adapted the
381 size of the perforation to that of the bead, possibly to reduce the risk of breakage. The three
382 specimens attributed to Type D have diameters incompatible with types A, B, E, and F, the two
383 ascribed to type E have diameters incompatible with Types A, B, D and F. Finally, the three beads
384 assigned to Type F, all from Layer 6, are significantly different in size and perforation diameter from
385 those belonging to all other types and two of them cluster with the circular marine shell bead
386 recovered in the same layer (see below). Of the eight OES beads falling outside the type range of
387 morphometric variability, one from Layer 7-8, displays, as with two of Type F, the same perforation
388 size of the circular shell beads found in that layer (Figure 3, n. 48), but falls at the very end of their
389 bead diameter variability. Similarly, another falls within the range of the perforation diameter of
390 Type B (Figure 5, n. 57). The other six beads have sizes incompatible with Types A, B, E, and F but
391 present a relatively large variation in perforation size.

392 In conclusion, the analysis of the OES beads found at Panga ya Saidi identifies discrete groups of
393 beads, each characterised by a combination of technological, stylistic, morphological and
394 dimensional features, plus a small group of OESBs, different from each other and from those
395 belonging to the main types.

396 Differences between Types A, B, C and E are striking and consistent, in the light of OES beads
397 variability observed ethnographically and archaeologically (d'Errico et al., 2012; Wei et al., 2017;
398 Pitarch Marti et al., 2017), with the interpretation of each of these groups of beads as having been
399 made by the same craftsman or crafts people sharing the same know-how, motions, and
400 aesthetic. It is possible some beads belonging to the same type originate from the same beadwork,
401 partially lost or deliberately disposed of at the site. The beads not allocated to specific types likely
402 represent objects coming from different beadworks and individually lost at the site. A possible
403 exception is represented by the bead dimensionally clustering with Group A and sharing other

404 features with the beads from this group (Figure 5, n. 57), but presenting an irregular outline. This
405 bead could belong to this group in spite of its idiosyncratic shape. The fact that single specimens
406 belonging to Types A, B and C are found in neighbouring layers may be due to mobility across layers
407 or fuzzy limits between the cultural traditions represented in these layers and Layers 7-8. OES beads
408 of Type F and the small bead falling, morphometrically, outside this group (Figure 3, n. 48), tell a
409 different story. They come from layers dated to historical periods and mostly fit into the
410 morphometric variability of relatively standardized circular beads made of marine shells (see
411 below). This suggests that during this recent period, OES became a raw material to produce beads
412 comparable in size to those made of marine shell.

413 *Perforated marine gastropods*

414 Five perforated marine gastropods (Table 3) were recovered at Panga ya Saidi: one *Volvarina* sp.
415 in Layer 11 (Figure 8, n. 1), two others in Layer 4 (Figure 3, n. 47) and Layers 1-2 (Figure 3, n. 5), one
416 perforated *Cypraea annulus* in Layer 3 (Figure 3, n. 28) and one *Cypraea moneta* in Layer 2 (Figure
417 3, n. 15). The three *Volvarina* sp. are, despite their different stratigraphic provenances, relatively
418 comparable in size and exhibit on their dorsal aspect similar elongated perforations aligned along
419 the shell longitudinal axis. The perforation edges have irregular, micro denticulate outlines,
420 suggesting that the perforation was enlarged by exerting pressure with a pointed tool on the
421 perforation edge (Figure S8). This technique was probably also employed to produce the large
422 irregular perforation on the *C. annulus* from Layer 3. The smaller off-centred perforation on the
423 shell from the same genus found in Layer 2 was instead opened by first creating a large facet by
424 abrasion and subsequently opening a hole by puncturing the dwindled shell wall (Figure S9).
425 Abrasion was also applied, on this shell, on the surface surrounding the facet on which the
426 perforation was made and on the outer lip, which exhibits striations oriented along the shell main
427 axis. All the perforated gastropods bear traces of utilization indicating that they were lost or
428 disposed of after being used as personal ornaments.

429 *Manufactured shell beads*

430 Forty small disk or cylindrical shaped shell beads and a possible unfinished bead were recovered at
431 Panga ya Saidi (Table 2; Figures 3-4). With the exception of two specimens, found in Layer 5, all the
432 others come from Layers 1-4. The possible unfinished bead is one of the two from Layer 5 (Figure 4,
433 n. 3), and it consists of a tubular undetermined fossil exhibiting a hole at one end and no compelling
434 evidence of deliberate modification. All the other beads bear diagnostic evidence of human
435 manufacture. Most of these beads were correctly identified as made of marine shell at the moment
436 of discovery. A number of them, however, black to dark-brown in colour, were tentatively interpreted
437 in the field as made of stone, possibly slate or shale. In order to determine the raw material, Raman
438 analysis were conducted on four of these latter beads (Table 2). Results indicate in all cases that the
439 main component is calcite (Raman bands at 155, 281, 712, 1085, 1260, 1298 and 1437 cm^{-1}), which
440 rules out slate, and is consistent with their production from marine shell (Figure S10). Raman analysis
441 also identifies, in two cases, the presence of amorphous carbon (bands 1351 and 1600 cm^{-1}), and in
442 one case the presence of anatase (TiO_2 , Raman bands at 147, 199, 398, 515, 638 cm^{-1}). Incorporation
443 of amorphous carbon is the consequence of heat treatment in a reductive environment conducted
444 with the aim of blackening the beads (d'Errico et al., 2015). This may also explain the absence of
445 aragonite. If naturally present in the shell, this mineral, was transformed to calcite by the heating
446 process. Incorporation of anatase could result from the use of a tool or an abrasive powder made of
447 a titanium rich-rock to shape the bead prior to heating, or a substance incorporated during the heating
448 process.

449 Although the degree of modification undergone by these beads makes it difficult in a number of
450 cases to identify the type of shell used as a raw material and the technique of manufacture, some
451 Panga ya Saidi beads show features providing information on these topics. Three cylindrical beads
452 (Figure 3, n. 4, 27, 46) retain on their curved surface shallow depressions identified as the folds of
453 marine gastropod columellas. This indicates that these beads were made, as with pre-Columbian
454 examples from Illinois, by carefully chipping away the body whorl and spire of large marine

455 gastropods, incising and snapping the exposed columella, and shaping the resulting tubular blank by
456 grinding (Kozuch, 2007). These three beads show no evidence of heating, which suggests that, unlike
457 their pre-Columbian counterparts, fire was not used to weaken the body whorl before chipping it
458 away. Remnants of bivalve sculpture consisting of undulations or individual grooves are identified on
459 one side of many of the other beads (Figure 3, n. 6-10, 12-13, 18-19, 29, 31- 38, 49; Figure 4, n. 2;
460 Figure S11). This suggests that the technique used to produce these beads entailed, as with OES
461 beads, trimming fragments of marine bivalves, grinding them on a grooved stone, polishing them
462 and, in some cases blackening them by heating. The thickness of these beads, ranging from 0.5 to 4.1
463 mm, indicates that a large variety of bivalves were used to produce them. Morphometric analysis
464 (Figure 10) reveals, compared to OES beads groups, a wide size range associated with a relatively
465 narrow, although quite variable, perforation size interval. This pattern likely reflects episodes of loss
466 of single or multiple beads coming from many similar beadworks, produced originally by numerous
467 crafts people using slightly different drilling tools. The perforation size and its cylindrical morphology
468 suggest the use of a bow-drill, although two specimens exhibit elliptical holes that may result from
469 the use of a hand-drill.

470 *Long term morphometric trends*

471 In addition to the differences in OES bead technology, colour, and size mentioned above a general
472 trend toward a reduction in bead size is observed from the bottom to the top of the sequence (Figure
473 S12). Beads in Layers 7-8 are tightly clustered with maximum dimensions between about 7.5 and 9
474 mm, and Layers 5 and 6 demonstrate an overall reduction toward mean diameters of around 7 mm.
475 If all disk beads (OES and marine shell) are considered together, a dramatic reduction in bead
476 maximum dimension occurs with the Iron Age layers (1-4), when bead maximum dimensions plunge
477 to around 4.5 mm.

478 **Worked bone**

479 Six objects made of bone and teeth bear clear evidence of deliberate modification (Table 3). Two
480 worked suid canines, probably tusks of bushpig (*Potamochoerus larvatus*) or warthog (*Phacochoerus*

481 *aethiopicus*) come from Layer 10 and one from Layers 7-8 (Figure 6, n. 11; Figure 7, n. 20-21). The first
482 two are fragments of tusks, longitudinally split before being manufactured by scraping on the resulting
483 break (Figure S13). Although the fragments are too small to establish with certainty what kind of tool
484 was sought, the pointed outline of one fragment suggests it may have been an awl. The piece from
485 Layers 7-8 is a fragment of a tusk tip preserving portions of the anterior, lingual and labial outer
486 surfaces covered by enamel, the masticatory surface, and a longitudinal break (Figure S13). In adult
487 wild suids, canine masticatory surfaces are generally covered with parallel striations, mimicking
488 grinding, perpendicular or slightly oblique to the main axis of the canine (d'Errico et al., 2012). In this
489 case, the remnant of the masticatory surface is covered by striations produced by scraping, parallel to
490 the tooth long axis. In addition, this surface is obliquely crossed by a deep groove made by a stone
491 tool, which may have been used to facilitate the longitudinal splitting of the tusk. Similar tools have
492 been reported from Border Cave, South Africa from MSA and early LSA layers dated to between 60 ka
493 and 44 ka (d'Errico et al., 2012). Another category of artifacts found in Layer 9 is represented by a
494 single specimen (Figure 7, n. 14; Figure S14). This is a mesial fragment of a thin point made of a small
495 mammal long bone, shaped by scraping. Diameter and technique of manufacture are consistent with
496 the interpretation of this object as a fragment of an arrow point comparable to those found at a few
497 early LSA sites in southern Africa (d'Errico et al., 2012; Backwell and d'Errico, 2016; Backwell et al.,
498 2018, but see Bradfield, 2016), ubiquitous at later LSA sites, and still in use among historical San
499 hunter-gatherers. Shot with small bows, these arrow points are generally covered with poison in order
500 to be effective when hunting large mammals.

501 Four objects from Layer 9 and Layers 7-8 are either fragments of decorated bone tubes made of
502 small mammal limb bones or byproducts of their manufacture (Figure 7, n. 1-2; Figure 6; n. 12-13).
503 The two fragments from Layer 9 do not refit, but judging from their similar thickness and manganese
504 stain pattern, may have originally been part of the same artifact. The larger fragment exhibits a set of
505 eighteen equidistant notches. The second has a set of eleven. Microscopic analysis indicates that each
506 set was made by a single tool, likely during a single episode (Figure S15). The lithic tool was in both

507 cases a straight unretouched cutting edge, as indicated by the narrow, asymmetrical section of the
508 notches and absence of steps on their angled side (d'Errico, 1998). The two objects from Layers 7-8
509 are a bone tube decorated on one side with two sets of notches and the epiphyseal fragment of a long
510 bone bearing a groove obliquely cutting the diaphysis. The latter is likely the leftover of an
511 unsuccessful attempt to produce a bone tube by first cutting a deep perpendicular notch around the
512 diaphysis and then snapping it by flexion (Figure 6, n. 12). The former is a fragmentary bone tube
513 bearing evidence at the preserved end of having being produced with the same technique (Figure 6,
514 n. 13). The sets of notches cut on this object were originally composed by at least eight and eleven
515 notches each. Both sets were likely made by the same tool during a single episode (this interpretation
516 is made on the basis of a photograph, as this object was unfortunately lost by the courier during
517 export).

518 **Fossil**

519 Layer 9 yielded a mesio-distal fragment of the rostrum of a belemnite exhibiting at its ends an old
520 and a recent fracture (Figure 7, n. 13). The longitudinally-oriented groove, corresponding to the
521 remnant of the siphon located on the back side of the rostrum, presents no trace of modification. The
522 object is highly polished and traces of abrasion are detected close to the ancient break (Figure S16).
523 Although no comparative material was available to characterize the natural appearance of rostra from
524 geographically close paleontological outcrops, the unusual polish suggests that the object was curated,
525 and possibly used as a tool or an ornament. The missing, naturally pointed end may have been used
526 for piercing. Rostra were used as personal ornaments in the Upper Paleolithic of Europe (Vanhaeren
527 and d'Errico, 2006; Sinitsyn, 2010). San people use similar objects, carved out of pebbles, with a slightly
528 wider groove, as arrow straighteners. The San peoples place them in hot sand before placing the arrow
529 shaft in the groove and gently bend it.

530 **Ochre pieces**

531 Seventeen lumps of ochre, yellow to dark red in colour, were identified as mineral pigments and
532 analyzed (Table 4). They come from Layers 7, 8, 10, and 16-18. Only two of them, from Layers 8 and
533 10, bear clear traces of modification (Figure 6, n. 14; Figure 7, n. 19). We provide below a description,
534 technological analysis and physicochemical characterization of these two last objects before
535 presenting results concerning the unmodified pieces. A summary of the results is given in Tables S1-
536 S3.

537 *Modified iron-rich pieces*

538 One piece of ochre from Layer 8 is a large fragment of an originally fully shaped iron-rich flat nodule
539 (Figure 6, n. 14; Figure S17). The largest triangular surfaces, corresponding to the nodule's original flat
540 sides, show evidence of having being shaped by pecking and polishing. The combination of these two
541 techniques produced a rough surface with pits and incipient fractures alternating with flat polished
542 areas that are covered by randomly oriented microscopic striations. Located between these two
543 surfaces, a flat area exhibiting two adjacent aligned facets is covered by subparallel striations oriented
544 along the nodule longest axis. They result from vigorous abrasion of this area against a lower
545 grindstone in a direction parallel to the nodule edge. The fracture that split the object served as a
546 platform to remove two small adjacent flakes that create a denticulated edge, as well as a point. The
547 latter bears microscopic evidence that it was used to mark a surface with thin red streaks. In summary,
548 this lump bears evidence of having been purposely shaped, used as a source of raw material to
549 produce a relatively coarse pigment powder, and split and retouched to be used as a crayon. The
550 shaping and multiple modifications and use suggest that the object was curated. The fracture reveals
551 a thick layer of fine-grain matrix crossed by randomly-oriented cleavages surrounding an amorphous
552 core. Under optical microscopy, the outer layer is composed of spots of dark red alternating with spots
553 of red fine-grained matrix. No visible grains are scattered within the matrix.

554 EDXRF elemental analysis identifies iron (Fe), calcium (Ca), manganese (Mn), and strontium (Sr)
555 and, at a trace level, phosphor (P), potassium (K), titanium (Ti), zinc (Zn), and yttrium (Y) (Figure S18).
556 SEM-EDS analysis indicates that the sample is composed of iron-oxide particles (Fe) associated with
557 silicates (Si) and aluminosilicates (Si, Al, K) (Figure S19). Most aluminosilicates take the form of sub-
558 micrometric particles (clay fraction). Micrometric particles are also identified, suggesting the presence
559 of micas and/or feldspars. Other elements detected by SEM-EDS include Mg, P, Ca, Ti and Mn. Raman
560 analysis identifies hematite (Fe_2O_3 , Raman bands at 222, 291, 403, 486, 605, and 1286 cm^{-1}), calcite
561 (CaCO_3 , main Raman band 1085 cm^{-1}), and quartz (SiO_2 , main Raman band at 459 cm^{-1}) (Table S2,
562 Figure S20). Intense fluorescence background and bands in the region between 1120 and 1415 cm^{-1}
563 suggest the presence of clay minerals. In some cases, a few weak bands appear in the region of 500 -
564 700 cm^{-1} , characteristic of Mn-O and Mn-OH bending and stretching vibrations. In addition, gypsum
565 - possibly a by-product of a weathering process - ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, Raman bands at 414, 493, 669, 1007
566 and 1027 cm^{-1}) - is also identified on the specimen surface.

567 A fragment from Layer 10, trapezoidal in shape, displays an angled edge along its longitudinal axis.
568 It exhibits on its convex aspect a set of wide joining grooves oriented along the main axis of the object
569 (Figure S21). Microscopic analysis indicates that the grooves were engraved by the same tool, in a
570 single episode, and that the craftsman deliberately terminated some lines or changed their direction
571 to create a recognizable pattern. This indicates that the lines were not made with the intent to produce
572 pigment powder. A few thin, parallel lines, oriented along the long axis of the object, are engraved on
573 the concave aspect of the piece. Two small opposing flake scars are located on one corner of its
574 narrower end.

575 Under optical microscopy, the fragment is composed of a dark red to orange compact
576 homogeneous clay with no grains scattered in the matrix. EDXRF elemental analysis identifies Fe, Ca,
577 and Mn, together with P, K, Ti, and Sr (Figure S22). SEM-EDS analysis indicates that the piece is
578 composed of iron-oxide particles (Fe) associated with silicates (Si), and aluminosilicates (Si, Al, K)
579 (Table S3, Figure S23). Silicates take the form of $5\text{ }\mu\text{m}$ wide or smaller rounded particles (Figure 28D-

580 E; Figure 29A). Most aluminosilicates consist of sub-micrometric particles (clay fraction), or, less
581 frequently, rounded micrometric tablets of micas and/or feldspars (see Figure S23 D and E, spectrum
582 SP1). Iron-oxides take the shape of sorted and rounded 2.5 μm wide particles (Figure S23 D-E,
583 spectrum SP2). Other elements present in the object matrix include carbon (C), magnesium (Mg), P,
584 sulphur (S), Ca, Ti, and Mn. The spatial distribution of the detected elements (Figure S24) shows that
585 Al is mostly associated with Si, but also with Fe. Ca is associated with P, and Mg. Mn is homogeneously
586 distributed and associated with Fe. In addition, the mapping identifies particles mostly composed of
587 C and S (Figure S23 D-E-SP3 and Figure S24) possibly biological in origin. Raman analysis finds hematite,
588 calcite and quartz as well as bands between 1120 and 1415 cm^{-1} , characteristic of clay minerals (Table
589 S2, Figure S25).

590 The finer-grained texture of the piece from Layer 10 compared to that from Layer 8, the lower
591 content in Ti and Mn, the presence of C, and the absence of Y indicate that these two objects may
592 come from different sources.

593 *Unmodified iron-rich rock lumps*

594 Fifteen other fragments collected during the excavation as possible lumps of red ochre are all
595 significantly smaller than the two modified pieces, more friable, and present a coarser granulometry
596 (Figure 6, n. 9-10; Figure 7, n. 23-25; Figure 8, n. 2, 4-7; 9-12). They show a range in variation that
597 extends from ferruginous lutite to ferruginous fine and very fine sandstone. Colour, texture, grain
598 size, and mineral content suggest that nine different sedimentary rock types are represented
599 (Tables S1 and S2). Hematite is identified by $\mu\text{-RS}$ in half of these lumps (Table S2). A number,
600 particularly those orange to dark red in shade, have clear colouring power. Some of these fragments
601 may derive from crushing larger lumps to produce pigment powder. This hypothesis would be
602 reinforced by the demonstration that these materials, or at least some of them, do not occur
603 naturally in the site sediment.

604 **Discussion and conclusion**

605 The analysis of several categories of key artifacts recovered from Panga ya Saidi opens up new
606 opportunities to explore how the material culture of populations living in the coastal areas of eastern
607 Africa integrated, since 78 ka, innovations reflecting the emergence of behaviorally 'modern' cultures.

608 The inferences that can be drawn from this material are limited by the fact that certain types of
609 objects, present in large numbers in a number of layers, were discovered in older layers exclusively in
610 the form of a single specimen or specimens that do not show diagnostic traces of modification. It may
611 therefore be premature to take their earliest occurrence in the stratigraphy as definite evidence that
612 the behaviours associated with these objects are contemporary with the layer in which they first
613 appear. The iron oxide rich fragments from Layers 18-16 may indicate that red pigment was brought
614 and perhaps processed at the site between 76 ka and 67 ka, but to be able to affirm this with certainty
615 in the absence of traces of modification on these objects, it would have to be demonstrated that this
616 material is not naturally present at the site, which requires dedicated work in the field and additional
617 analyses.

618 While the bulk of the Panga ya Saidi assemblage does not represent 'earliest' occurrences of
619 osseous tools and symbolic artifacts, it does provide a unique record for deep-time behavioural
620 patterns leading to intensification of important phenomena like bead production. Furthermore, the
621 high-resolution palaeoecological record for the site and the emerging datasets on stone tools and
622 other materials offer great potential to understand the context for the emergence of symbolic traits.
623 If these circumstances can be reconstructed from the Panga ya Saidi dataset, it may offer new
624 analogical structures for investigating "earliest" occurrences and testing hypotheses relating changes
625 in symbolic styles with changes in population structures. The Panga ya Saidi assemblage itself adds an
626 important data point to an emerging picture of diverse symbolic trajectories through the MSA and LSA
627 of eastern Africa.

628 The first definite evidence of an interest in ochre use appears in Layer 10 (between 48.5-33 ka, for
629 Layers 11-9). Such interest is manifested by the use of an ochre fragment as a media for engraving

630 rather than for intense extraction of colour powder, the latter of which is only demonstrated by an
631 object in Layer 8 (ca. 25 ka). A similar caveat applies to the only puka shell found in Layer 16 (bracketed
632 by dates of 67 ka – 61.5 ka) and the perforated *Volvarina* sp. discovered in Layer 11 (48.5 ka). The first
633 layers in which several puka shells appear in association are Layers 9 (33 ky) and 8 (25 ka), and the
634 other two *Volvarina* sp. shells discovered so far come from Layer 4 (7.5 ky) and Layers 1-2 (ca. 1 ka),
635 and have a perforation very similar to the specimen from Layer 11. This raises the question as to
636 whether puka shells are an ornament that emerged in this region in the late MSA (67-61.5 ka) or
637 whether their appearance is contemporary with the first OES beads, around 33 ka. In the former
638 scenario, it would be the first indication that marine shell beads preceded OES beads in eastern Africa
639 in a pattern more comparable to that seen in southern Africa. If the latter is supported by future
640 evidence, the sudden investment in forms of exo-somatic symbolism may reflect major changes in
641 demographic dynamics at this time. What is clear is that these puka shells were certainly used as
642 ornaments between 33 ka and 25 ka, and that they are absent in Layer 6 (>25 ka) in which OES beads
643 are found. Additionally, Panga ya Saidi is the first site in which they are found in Africa, making them
644 an icon of the cultural trajectory of the coastal populations of the region.

645 Almost all typical OES beads come from Layers 5-8 (25-14 ka). The single specimens from Layer 9
646 (33 ka) and Layers 2-4 may indicate sporadic loss of this ornament type contemporaneous with the
647 deposition of those layers or post-depositional displacement. The second hypothesis is reinforced for
648 the more recent specimens by the presence, in those layers, of numerous tiny circular beads, some of
649 which are made of OES, so that the two larger OES beads found in those layers are idiosyncratic
650 occurrences. The alternative hypothesis is that during the deposition of recent layers the site was
651 alternatively occupied by users of both bead types or that the occupants of the cave used both bead
652 types. If the stratigraphic distribution of bead types is confirmed by the analysis of the material from
653 the more recent excavation seasons at Panga ya Saidi and at other sites, this may indicate that OES
654 beads were first in use in some coastal regions of East Africa later than in inland areas, the earliest

655 occurrences of this bead type being dated in Kenya, Tanzania and South Africa between 50 ka and 31
656 ka (Miller and Willoughby 2014; see Wei et al., 2017 for a synthesis).

657 The absence of ostrich remains, egg shell fragments, bead preforms, the intense use-wear recorded
658 on all OES beads and the numerous specimens bearing ochre residues suggest that the beads were
659 lost or disposed of, but not manufactured at the site, at least in the spatial locality investigated by our
660 trench. The current distribution of the two ostrich species that probably provided the eggs from which
661 the beads discovered at Panga ya Saidi were produced is limited to grassland plateaus, the closest of
662 which occur today about 100 kilometres west of the site (Sinclair, 2003). It is unlikely, in light of climate
663 model outputs for the LGM (Shipton et al., 2018), that grasslands have spread, even in drier periods,
664 to coastal areas. This is consistent with our results and, together with the fact that Panga ya Saidi is
665 the only site in eastern Africa with a bead assemblage that lacks any indication of early stage working
666 or preforms, suggests that OES beads should be considered exotic items at Panga ya Saidi. Clear
667 differences in OES beads technology, size, style, and heat-induced colouring indicate that different
668 human groups carrying different variants of these ornaments visited the site during the deposition of
669 Layers 5-8; that one group had access to the traditions of different groups through exchange; or that
670 one resident group employed two different traditions of OES bead manufacture.

671 The OES beads from Panga ya Saidi also demonstrate a trend toward smaller diameters through
672 the sequence, similar to the size reduction noted for the Pleistocene layers at Kisese II (Tryon et al.,
673 2017). This dramatic discontinuity in bead material and size may be the best evidence for changes in
674 population structure. It is interesting to note in this respect that an individual burial from the site
675 dating to 400 BP retains strong East African forager ancestry (Skoglund et al., 2017).

676 However the bead manufacture and size patterns are interpreted, they appear to be unique for
677 eastern Africa and may reflect the coast experiences different cultural influences, developments or
678 population histories relative to inland areas. Hypotheses that needs to be explored in this regard are
679 that puka shells may reflect the identity of coastal populations before the spread of OES beads into
680 these areas, and that the site has been occupied or visited during at least some periods by different

681 populations, some wearing puka shells and others OES beads, or that the people frequenting the site
682 were wearing both. Whatever the case, a clear shift in bead technology and types occurs at the
683 beginning of the Holocene, when small circular beads made of marine shells and OES, perforated
684 cowrie and *Volvarina* shells, and small tubular beads made of the columellas of large marine
685 gastropods replace large OES beads. An important caveat is that many older excavations in the Central
686 Rift Valley employed 5mm screen sizes, and so some bead size distributions may have be biased.

687 The only other Pleistocene African site that has yielded worked suid tusks is Border Cave (d'Errico
688 et al., 2012), where they were processed with techniques similar to those identified at Panga ya Saidi
689 and mostly occur in layers roughly contemporaneous with those in which they are found at Panga ya
690 Saidi. At Border Cave, however, a few pieces come from older, 60 ka layers, while the artifact from
691 Panga ya Saidi comes from Layer 7-8 (25 ka). At Border Cave, as at other early LSA sites from Southern
692 Africa (Backwell et al., 2012; Backwell and d'Errico 2016), we find the two other bone artifact
693 categories identified at Panga ya Saidi: bone diaphyses carrying sets of notches, and thin bone artifacts
694 interpreted as pins or possible arrow points used with poison (d'Errico et al., 2012; Backwell et al.,
695 2018). The peculiarity of the Panga ya Saidi objects belonging to the first category lies in the fact that
696 two of them bear clear traces of having been cut with the groove-and-snap technique to produce bone
697 tubes that may have been used as containers, and that the set of notches have been apparently made
698 by a single tool and in an attempt to juxtapose them equidistantly, which points to a decorative rather
699 than notational function (d'Errico et al., 2018). Although the bone rod found in Layer 9 is broken,
700 making it difficult to attribute this object to an artifact category, its diameter falls in the variability of
701 LSA and historical bipointed arrowheads from southern Africa (d'Errico et al., 2012; Robbins et al.,
702 2012).

703 Bone implements and especially the notched piece artifact in Pleistocene contexts are typologically
704 and temporally similar to those reported for Kuumbi Cave on the Tanzanian coast (Langley et al.,
705 2016). Taken together, the Panga ya Saidi and Kuumbi Cave datasets indicate a tradition of bone tool
706 production and use by c. 20,000 BP on the coast of eastern Africa that predates any comparable

707 pattern inland by nearly 10,000 years. The early appearance of worked bone traditions on the coast
708 relative to inland is an interesting contrast to the apparently opposite pattern discussed above for OES
709 beads.

710 When evaluated in a pan-African context Panga ya Saidi records the emergence, perhaps as early
711 as 67 ka or at 33 ka, of an original symbolic material culture (puka shells) replaced, possibly later than
712 elsewhere, by symbolic items (ostrich egg shell beads) and bone artifacts (worked suid tusks, small
713 bone point, notched bone containers) showing similarities with those identified at sites in southern
714 Africa located in subtropical areas, such as at Border Cave and Sibudu. The identified trend is
715 consistent with a more fragmented cultural geography until ca. 40 ka, followed by the adoption of
716 cultural innovations that may have emerged in neighbouring regions and arrived by cultural diffusion
717 to East Africa. OES beads, in particular, suggest the creation of exchange networks with inland areas.
718 These are replaced, at the beginning of the Holocene, by a more varied body ornamentation primarily
719 exploiting marine resources that includes bead types whose production required a degree of craft
720 specialisation.

721 It is therefore clear that the processes initiated by the first appearances of symbolic behaviours in
722 the MSA are not part of a single event, but rather cascading shifts toward in regional connections and
723 diversifications over many millennia. Further investigation is needed to understand the degree to
724 which this may reflect growing biological or ethnic boundaries among Pleistocene foragers.

725 In summary, Panga ya Saidi is important as it is, at present, the only site located outside north-west
726 and southern Africa, the two classic regions in which key cultural innovations have been identified in
727 MSA contexts, to deliver, in a well dated sequence, a record of cultural innovations of diverse types
728 over a time span covering the late MSA and the LSA. Together, the results highlighted here are
729 consistent with a scenario in which both regional trajectories and cultural/demic diffusion acted, at
730 different times, as the driving factors shaping cultural diversity in Africa. Ongoing analyses of material
731 from recent excavation campaigns at Panga ya Saidi and other sites will allow testing of the patterns

732 identified here, and further document the emergence and long-term evolution of personal ornaments,
733 bone technologies, and ochre use in eastern Africa.

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1111 **Figure captions**

1112 Figure 1. Location of Panga ya Saidi with the orography of the region and sea level at -125 m along
1113 the modern shoreline.

1114 Figure 2. Panga ya Saidi sections indicating limits between layers and units, selected features, and
1115 the sequence chronology.

1116 Figure 3. Personal ornaments from Layers 1-4. Scale = 1 cm.

1117 Figure 4. Personal ornaments from Layers 5-6. Scale = 1 cm.

1118 Figure 5. Ostrich egg shell beads from Layers 7-8. Scale = 1 cm.

1119 Figure 6. Personal ornaments (n. 1-8), possible lumps of pigment (n. 9-10), worked tusk fragments
1120 (n.11), worked bones (n. 12-13), and heavily modified ochre lump (n. 14), all from Layers 7-8. Scale
1121 = 1 cm.

1122 Figure 7. Worked bones (n. 1-2, 14), worked suid tusks (n. 20-21), personal ornaments (n. 3-12, 15-
1123 18), rostrum of belemnite (n. 13), engraved lump of ochre (n. 19), possible ornament (n. 22) and
1124 ochre lumps (n. 23-25) from Layer 9. Scale = 1 cm.

1125 Figure 8. Perforated *Volvarina* sp. from Layer 11 (n.1), possible lump of ochre and *Conus* shell fragment
1126 from Layer 16 (n.2-3), possible lumps of ochre from Layers 17 and 18 (n.4-12). Scale = 1 cm.

1127 Figure 9. Examples of OESBs identified as belonging to different types. Type A, B and C: OESBs from
1128 Layer 7-8 (context 412); Type D: OESBs from Layer 5 (context 104, spit F) (left) and Layer 6 (context
1129 104, spit G) (right); Type E: OESBs from Layer 5, (context 104, spit F) (left) and Layer 6 (context 104
1130 spit G) (right); Type F: OESBs from Layer 2 (context 406) (left) and Layer 3 (context 408, spit A)
1131 (right). Scale = 1 mm.

1132 Figure 10. Scatterplot correlating maximum bead and perforation diameters of circular marine shell
1133 beads and OESB. OESB different from each other and from main types are indicated in blue.

1134 Horizontal bands highlight differences in perforation size between marine shell beads, and OESB
1135 types A and B.

1136 **Supplementary materials**

1137 Figures

1138
1139 Figure S1. Top: Spiral fragments of *Conus* shells from Layer 9 (context 413, spit B (left) and spit C
1140 (center and right)). Bottom: comparable fragments from thanatocoenoses obtained from Southern
1141 African shores. Scale = 1mm.

1142 Figure S2. A: *Conus* shell from Layer 16 (context 420); Center: 3D reconstruction of the perforation
1143 (left), and an area close to the perforation showing horizontal grooves produced by coarse abrasion
1144 partially obliterated by vertical striations resulting from polish (right). B: *Conus* shell from Layers
1145 7-8 (context 104, spit H), with possible traces left by a tool used to enlarge the natural perforation.
1146 Scale = 1 mm.

1147 Figure S3. Close up-view of the ostrich egg shell outer face on OESB from Layers 7-8 (context 412).
1148 Variability in pore arrangements suggests the use of eggs of *Struthio camelus massaicus* (left) and
1149 *Struthio camelus molybdophanes* (right) (Schönwetter, 1927; Sauer, 1972). Scale = 1 mm.

1150 Figure S4. A and B: OESB from Layer 5 (context 104, spit F) (A), and Layer 3 (context 408, spit A); B:
1151 with traces of abrasion; C: OESB from Layer 2 (context 102, spit B), showing polishing of the
1152 mammillary layer; D: OESB from Layer 7-8 (context 412), preserving traces of rotation on the
1153 perforation edge. Scale = 1 mm.

1154 Figure S5. Examples of OESBs not falling in any of the six main OESB types. A, B, C and D are from Layer
1155 7-8 (context 412); E and F are from Layer 5 (context 104, spit F); G is from Layer 2 (context 102, spit
1156 B); H is from Layer 4 (context 408, spit B). Scale = 1 mm.

1157 Figure S6. OESB from Layer 7-8 (context 412) showing removal of a large portion of the outer egg shell
1158 surface due to heating. Scale = 1 mm.

1159 Figure S7. OESB from Layer 7-8 (context 412) exhibiting a thick red residue on the surface of the
1160 perforation. Scale = 1 mm.

1161 Figure S8. *Volvarina* sp. shell from Layer 4 (context 408, spit A), showing an elongated perforation
1162 enlarged by pressure. Scale = 1 mm.

1163 Figure S9. Top: *Cypraea moneta* from Layer 2 (context 407); bottom left and center: facet produced
1164 by grinding the body whorl surface in different direction before punching it in the middle; bottom
1165 right: subparallel striations produced by abrading the inner lip along the shell long axis. Scale = 1
1166 mm.

1167 Figure S10. μ -RS spectra on black beads from Layer 3 (context 408, spit C). A, see Figure 1, n. 39; B,
1168 see Figure 1, n. 40.

1169 Figure S11. A-B: marine shell beads from Layers 1-2 (context 402) (A), and Layer 3 (context 408, spit
1170 A) bearing cylindrical perforations and striations produced by flattening the bead surface. C: marine
1171 shell bead from Layer 3 (context 408, spit A), with an off-centre ovoidal perforation. B and C show
1172 remnant of bivalve sculpture. Scale = 1 mm.

1173 Figure S12. Stratigraphic variation in beads maximum diameter.

1174 Figure S13. Top and centre: fragments of warthog or bushpig tusks from Layer 10 (context 414, spit D)
1175 showing scraping marks; bottom: fragment from Layer 7-8 (context 412) showing scraping marks
1176 and a deep groove. Scale = 1 mm.

1177 Figure S14. Mesial fragment of a bone point from Layer 9 (context 413, spit C), showing longitudinal
1178 scraping (close-up view at the right). Scale = 1 mm.

1179 Figure S15. Notched bone fragments from Layer 9 (context 413, spit A). Scale = 1 mm.

1180 Figure S16. Mesial fragment of a belemnite rostrum from Layer 9 (context 413, spit C), showing traces
1181 of abrasion (close-up on the right)). Scale = 1 mm.

1182 Figure S17. Iron-rich nodule from Layer 8 (context 104, spit H) presenting a variety of modification
1183 traces (see text).

1184 Figure S18. Result of the EDXRF analysis of the Iron-rich nodule from Layer 8 (context 104, spit H)
1185 within the specimen from Layer 10, context 313, spit P. A: Location of the analyses. B: EDXRF
1186 spectrum. C: Detailed view of the spectrum.

1187 Figure S19. SEM-EDS analysis on the specimen from Layer 8 (context 104, spit H). A-B: Location of the
1188 analysis. C: Detailed view of B in BSE mode. D: Detailed view of C.

1189 Figure S20. μ -RS analyses on the specimen from Layer 8 (context 104, spit H). A-B: Location of the
1190 analyses. C-E: Raman spectra of different sub-areas.

1191 Figure S21. Engraved fragment of ochre from Layer 10 (context 313, spit P).

1192 Figure S22. Result of the EDXRF analysis of the engraved fragment of ochre from Layer 10 (context
1193 313, spit P) within the specimen from Layer 10 (context 313, spit P). A: Location of the analyses. B:
1194 EDXRF spectrum. C: Detailed view of the spectrum.

1195 Figure S23. SEM-EDS analysis on the engraved fragment of ochre from Layer 10 (context 313, spit P).
1196 A: Location of the analyses. B-C: SE and BSE mode images at a low magnification. D: Detailed view
1197 in BSE mode with the location of the analyzed spots. E: EDS spectra.

1198 Figure S24. SEM-EDS analysis of the engraved fragment of ochre from Layer 10 (context 313, spit P).
1199 Distribution of the main elements composing the analyzed area.

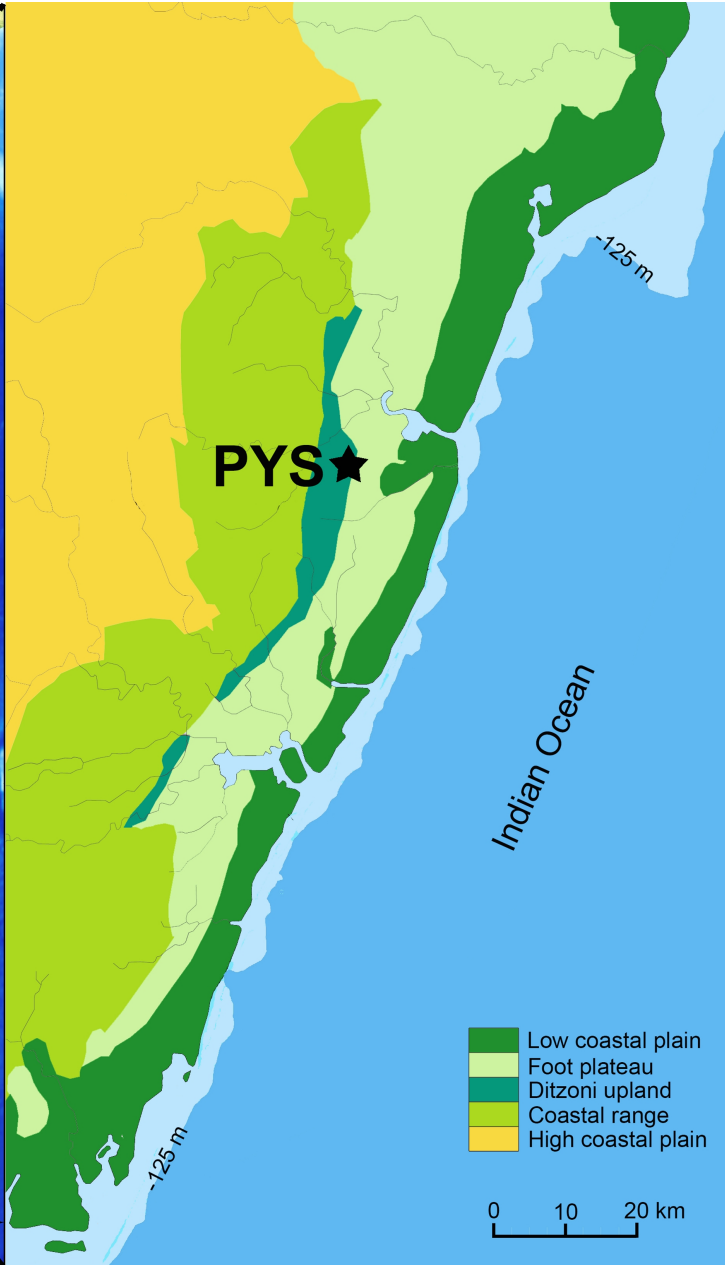
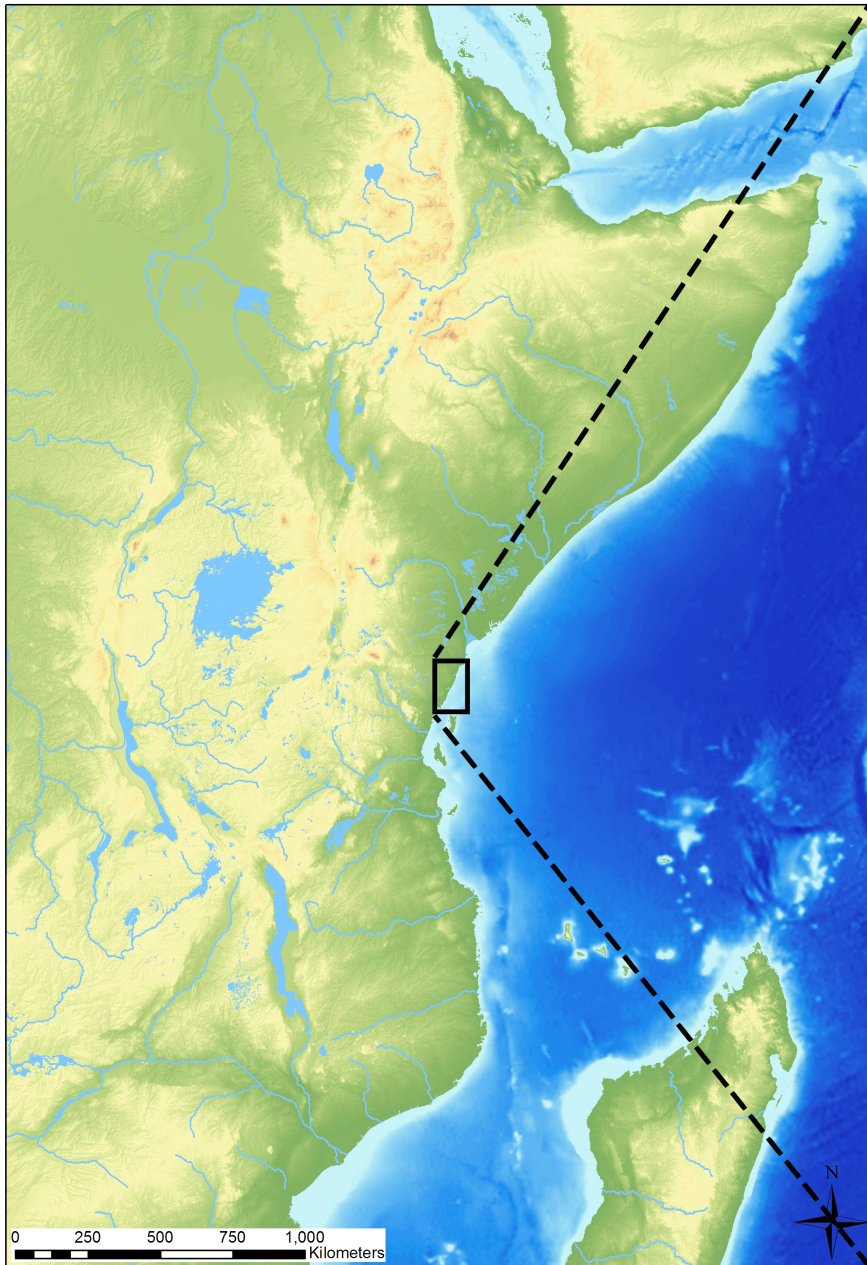
1200 Figure S25. μ -RS analyses on the specimen from Layer 10 (context 313, spit P). A-B: Location of the
1201 analyses. C-D: Raman spectra of different compounds.

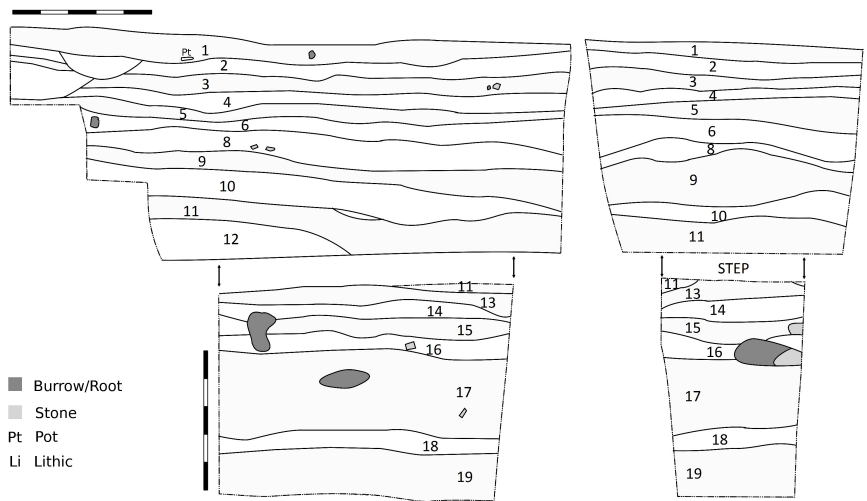
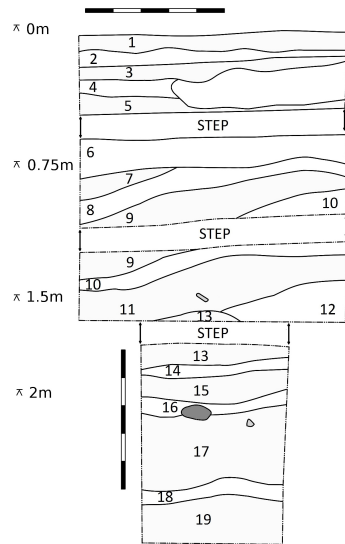
1202 Tables

1203 Table S1. Contextual data and results concerning the pigment analyses.

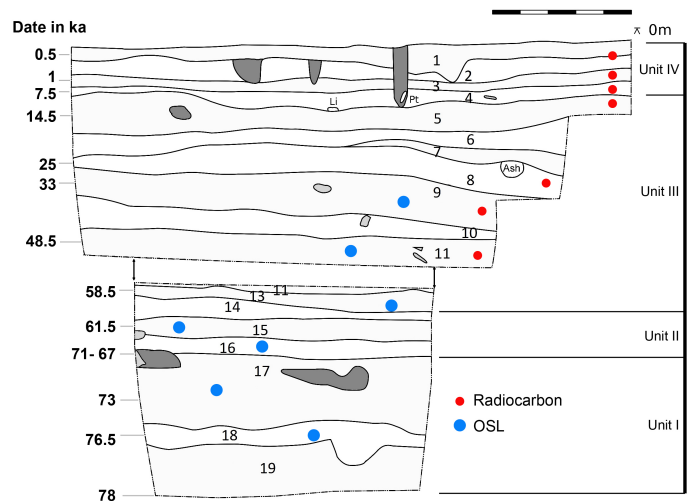
1204 Table S2. Results of μ -RS analyses on iron-rich lumps from Panga ya Saidi.

1205 Table S3. Results of semi-quantitative SEM-EDS analysis of modified ochre lump PYS-Phase4-Layer10-
1206 Context 313P





- Burrow/Root
- Stone
- Pt Pot
- Li Lithic



Layer 1



Layer 1-2



Layer 2



Layer 3



Layer 4



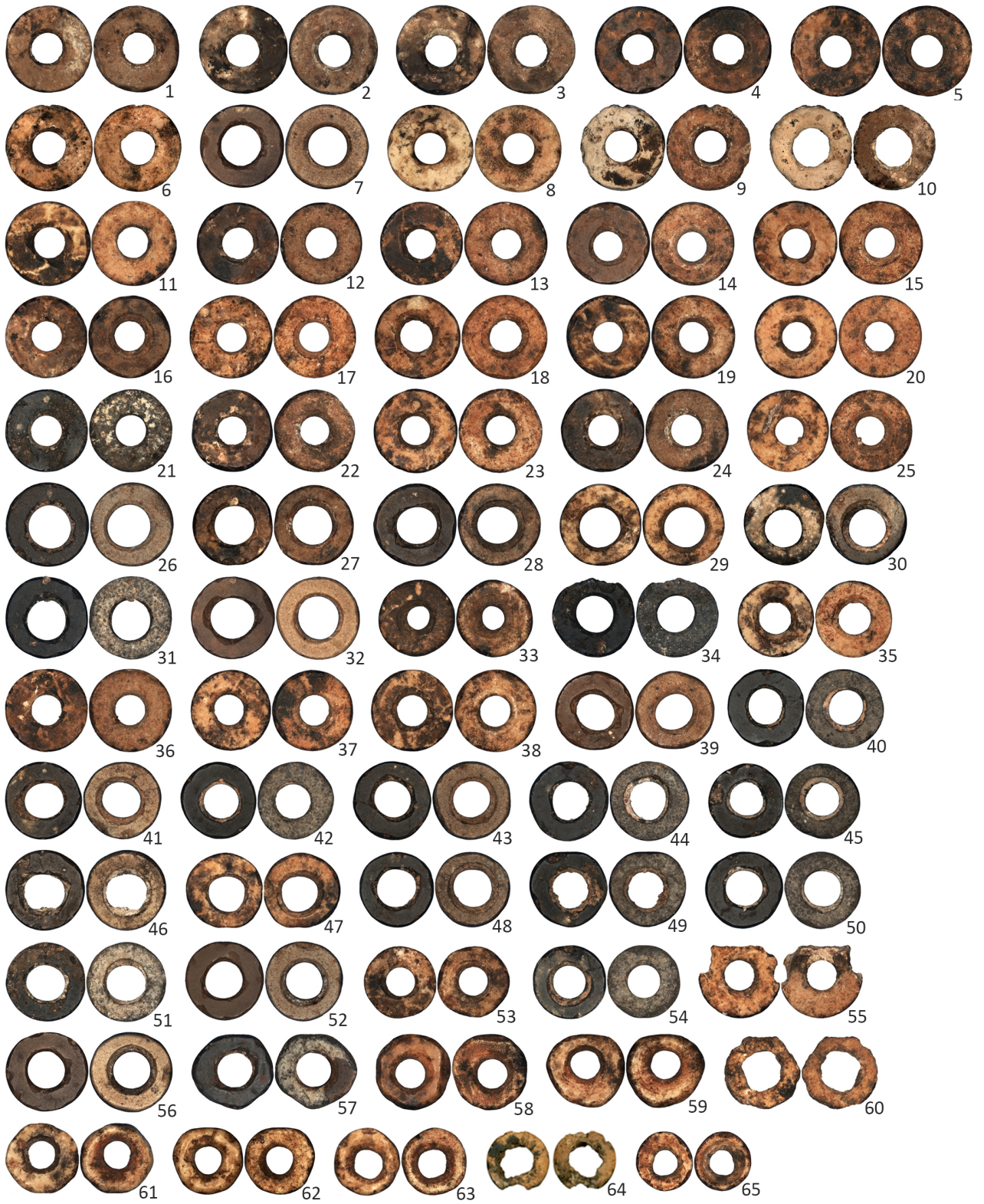
Layer 5



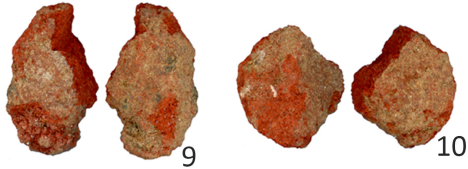
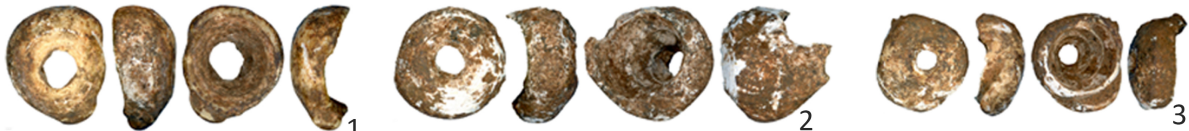
Layer 6



Layer 7-8



Layer 7-8



Layer 9



Layer 10



Layer 11



Layer 16



Layer 17



Layer 18



Type A



Type B



Type C



Type D



Type E



Type F



—

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Supplementary data

Figures S1-S25

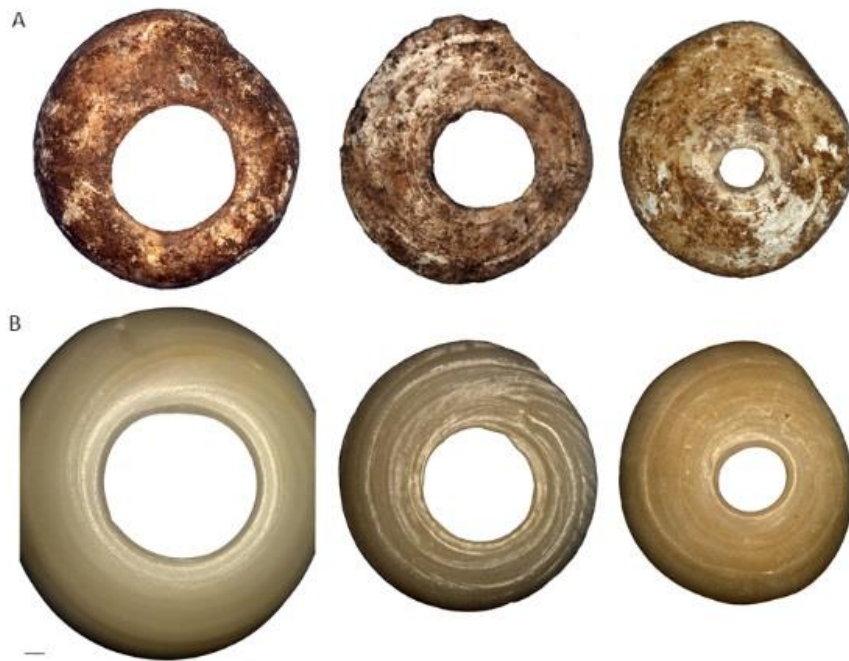


Figure S1. Top: Spiral fragments of *Conus* shells from Layer 9 (context 413, spit B (left) and spit C (center and right)). Bottom: comparable fragments from thanatocoenoses obtained from Southern African shores. Scale = 1mm.

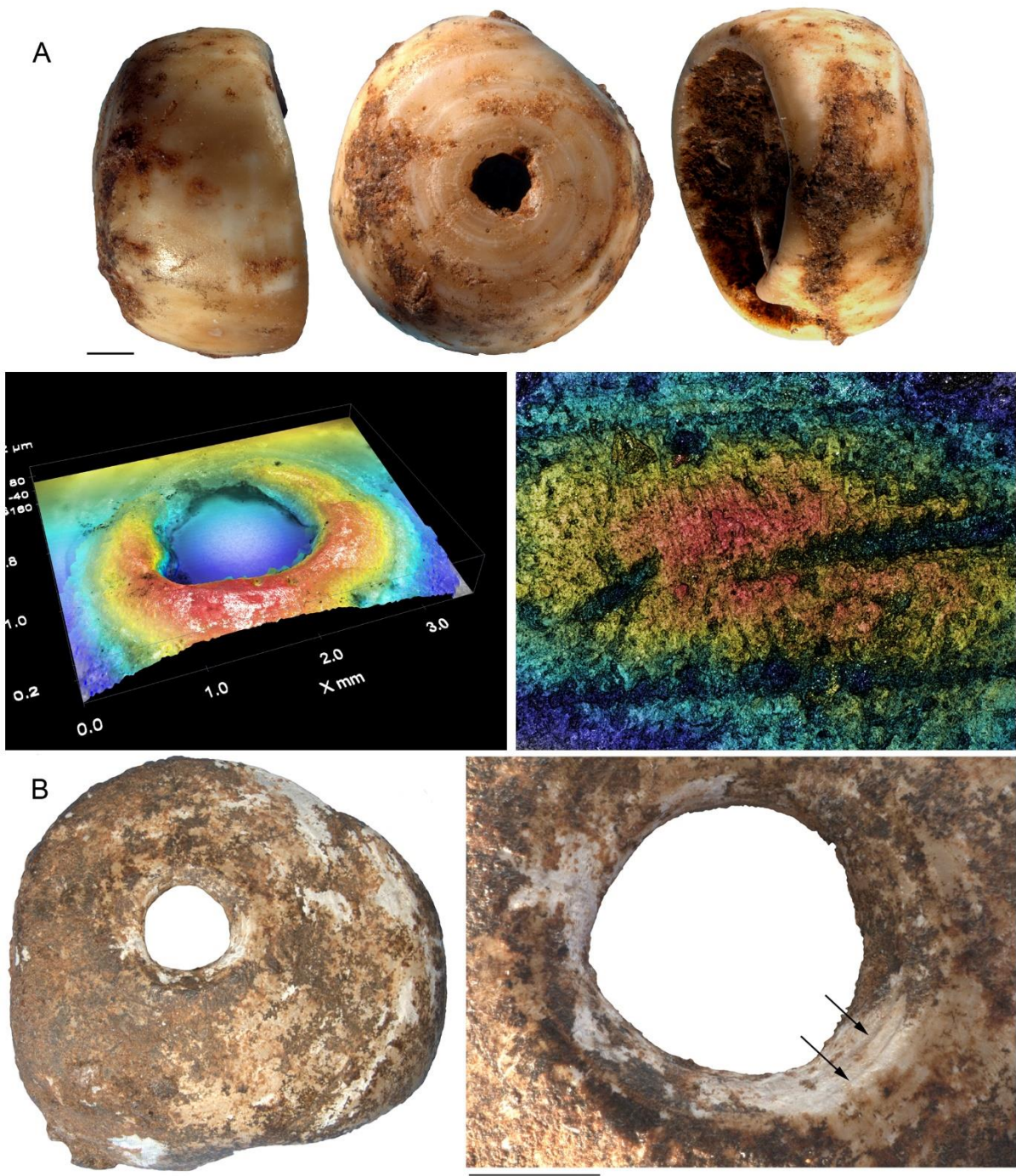


Figure S2. A: *Conus* shell from Layer 16 (context 420); Center: 3D reconstruction of the perforation (left), and an area close to the perforation showing horizontal grooves produced by coarse abrasion partially obliterated by vertical striations resulting from polish (right). B: *Conus* shell from Layers 7-8 (context 104, spit H), with possible traces left by a tool used to enlarge the natural perforation. Scale = 1 mm.

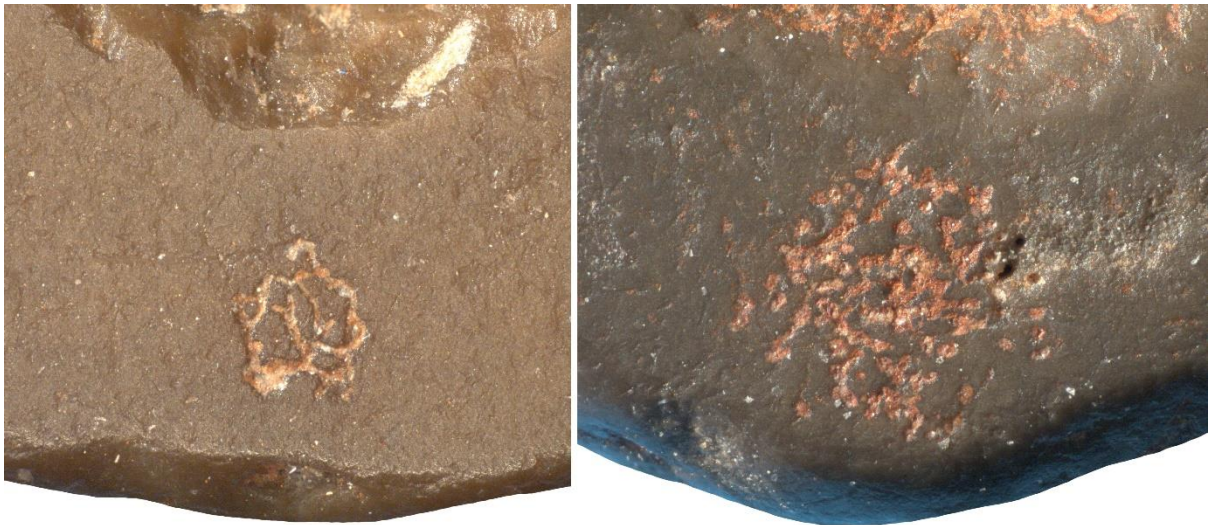


Figure S3. Close up-view of the ostrich egg shell outer face on OESB from Layers 7-8 (context 412). Variability in pore arrangements suggests the use of eggs of *Struthio camelus massaicus* (left) and *Struthio camelus molybdophanes* (right) (Schönwetter, 1927; Sauer, 1972). Scale = 1 mm.

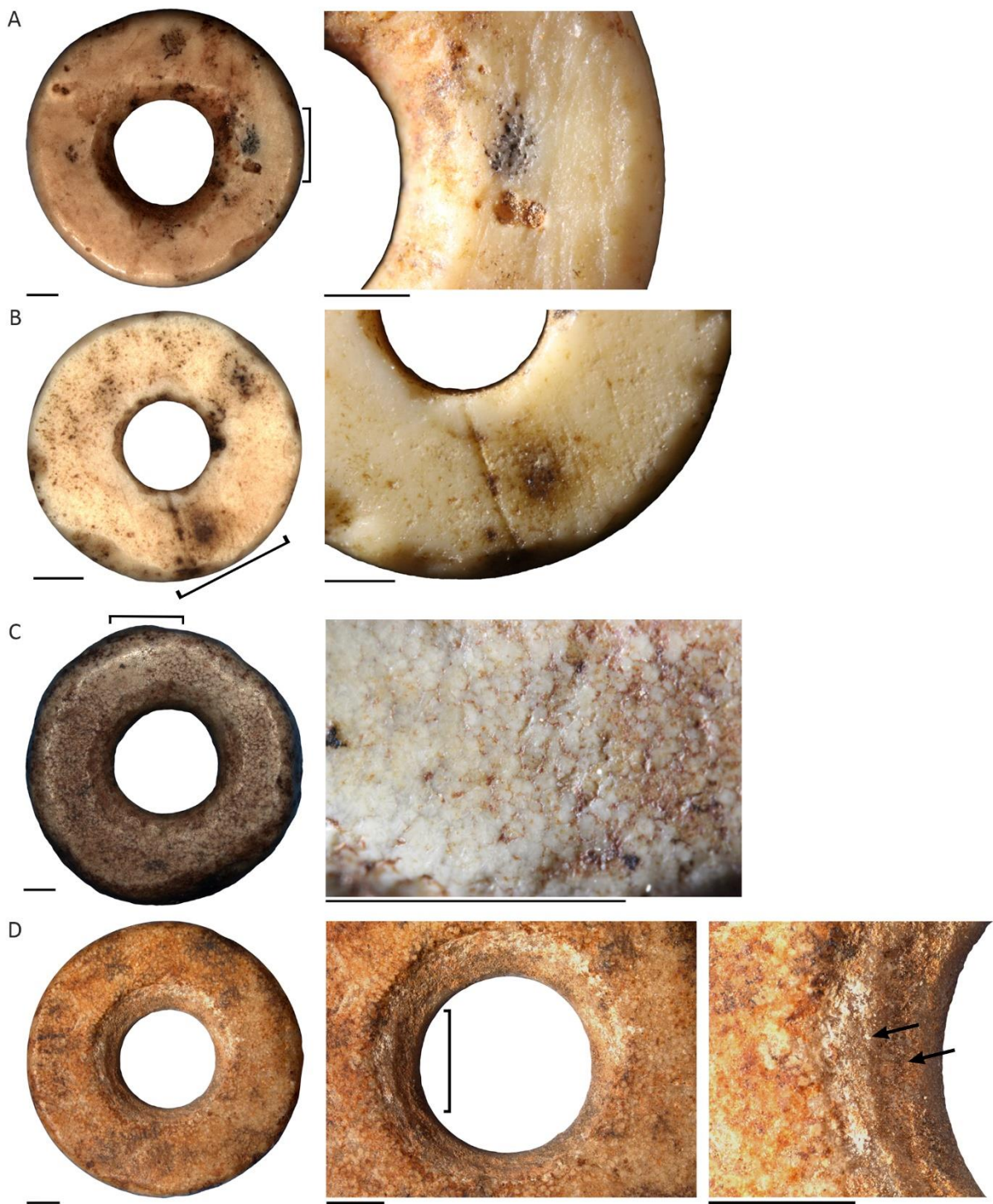


Figure S4. A and B: OESB from Layer 5 (context 104, spit F) (A), and Layer 3 (context 408, spit A); B: with traces of abrasion; C: OESB from Layer 2 (context 102, spit B), showing polishing of the mammillary layer; D: OESB from Layer 7-8 (context 412), preserving traces of rotation on the perforation edge. Scale = 1 mm



Figure S5. Examples of OESBs not falling in any of the six main OESB types. A, B, C and D are from Layer 7-8 (context 412); E and F are from Layer 5 (context 104, spit F); G is from Layer 2 (context 102, spit B); H is from Layer 4 (context 408, spit B). Scale = 1 mm.

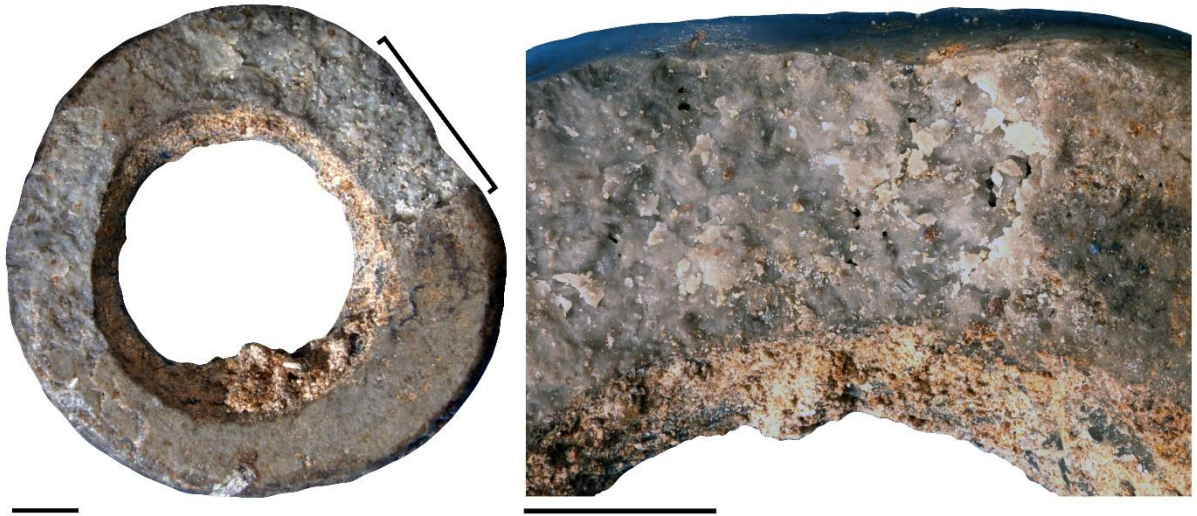


Figure S6. OESB from Layer 7-8 (context 412) showing removal of a large portion of the outer egg shell surface due to heating. Scale = 1 mm.



Figure S7. OESB from Layer 7-8 (context 412) exhibiting a thick red residue on the surface of the perforation. Scale = 1 mm.



Figure S8. *Volvarina* sp. shell from Layer 4 (con

text 408, spit A), showing an elongated perforation enlarged by pressure. Scale = 1 mm.



Figure S9. Top: *Cypraea moneta* from Layer 2 (context 407); bottom left and center: facet produced by grinding the body whorl surface in different direction before punching it in the middle; bottom right: subparallel striations produced by abrading the inner lip along the shell long axis. Scale = 1 mm.

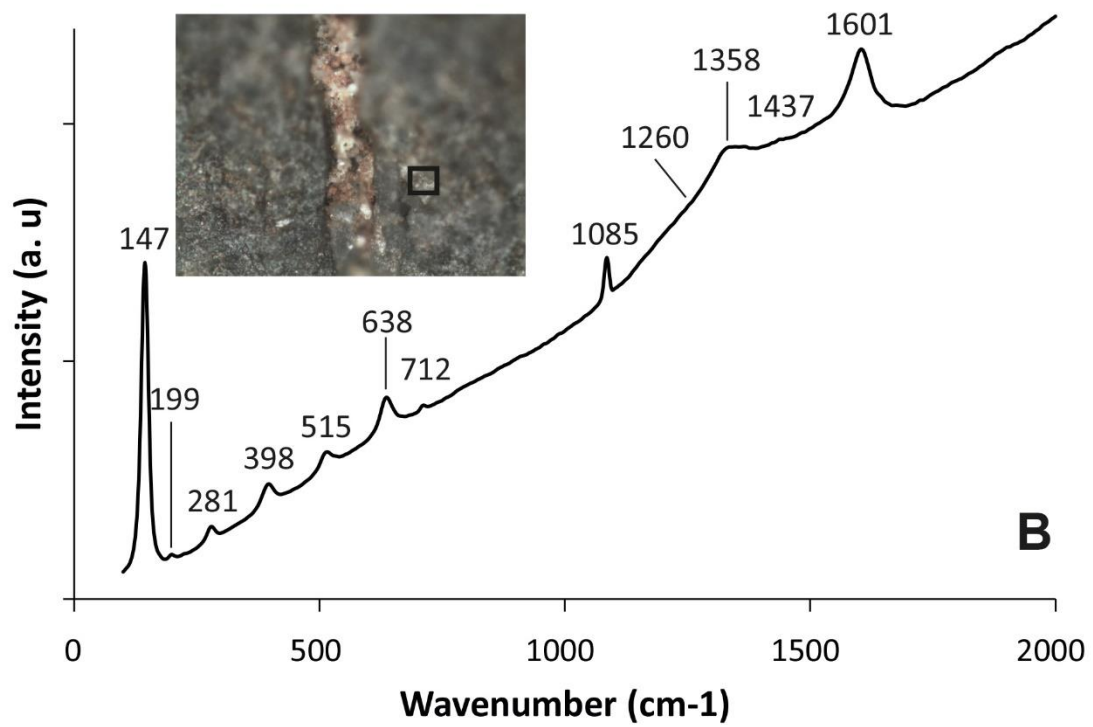
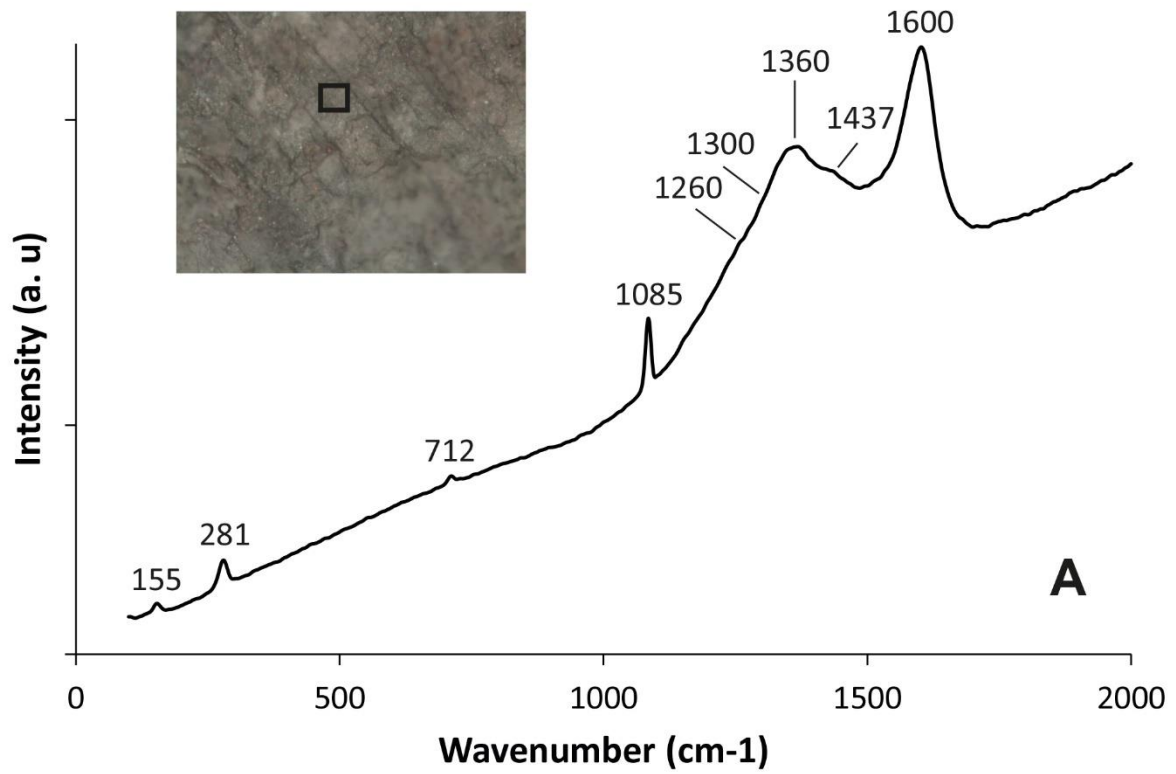


Figure S10. μ -RS spectra on black beads from Layer 3 (context 408, spit C). A, see Figure 1, n. 39; B, see Figure 1, n. 40.

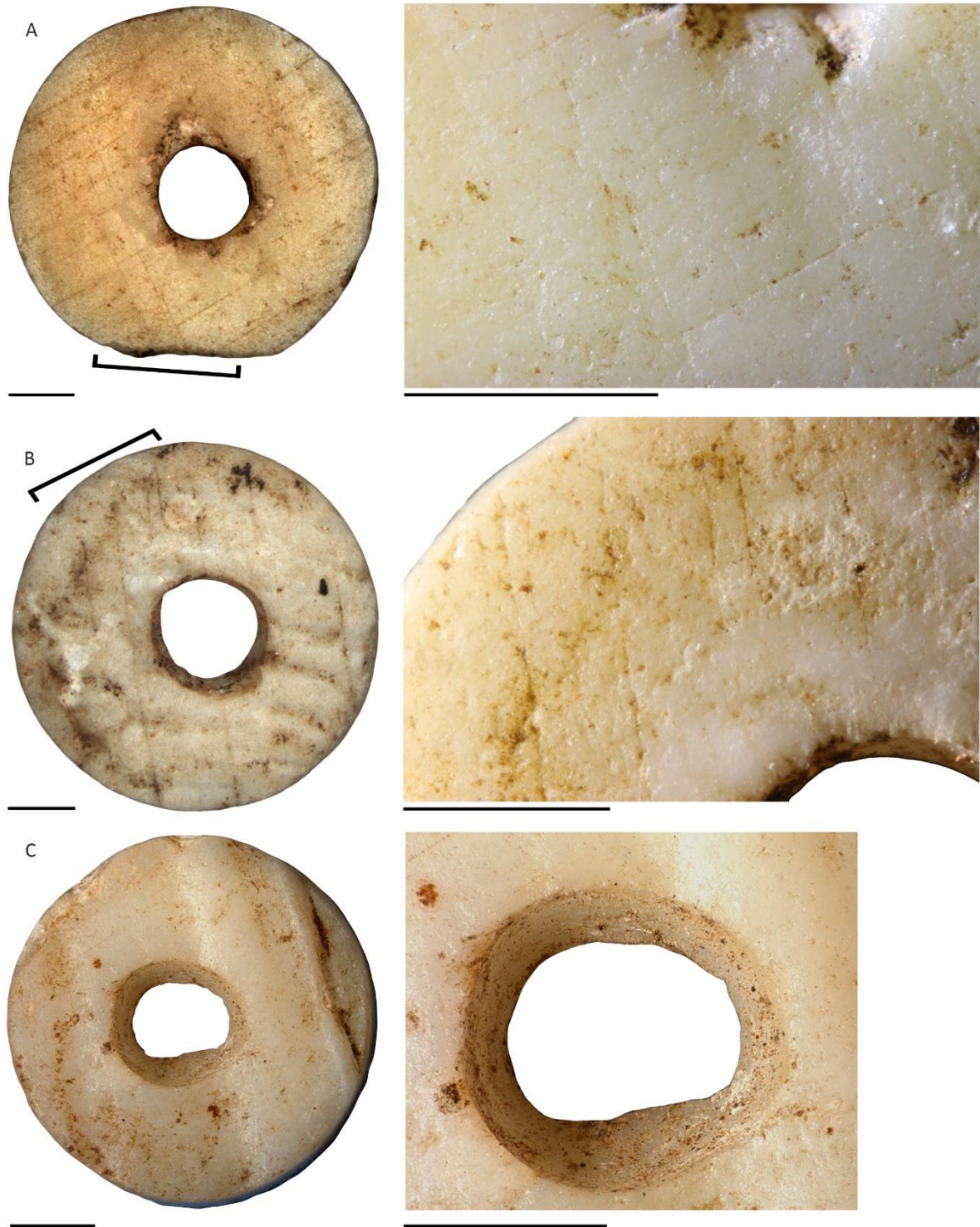


Figure S11. A-B: marine shell beads from Layers 1-2 (context 402) (A), and Layer 3 (context 408, spit A) bearing cylindrical perforations and striations produced by flattening the bead surface. C: marine shell bead from Layer 3 (context 408, spit A), with an off-centre ovoidal perforation. B and C show remnant of bivalve sculpture. Scale = 1 mm.

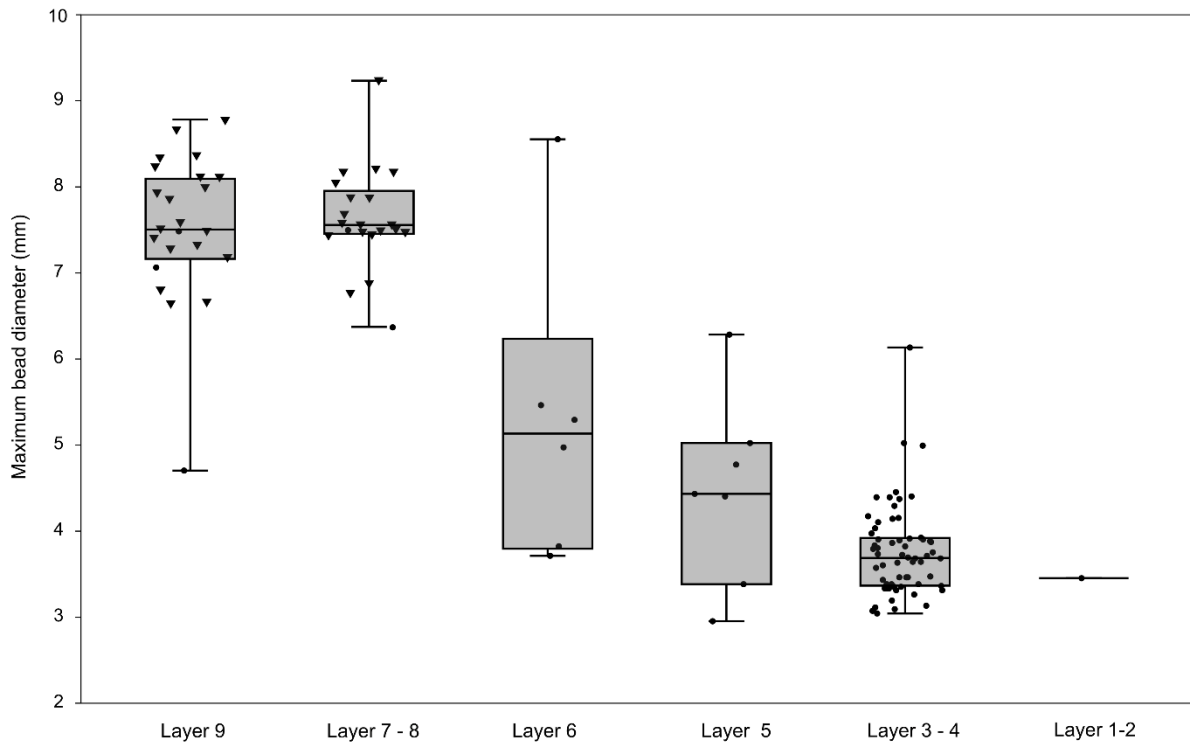


Figure S12. Stratigraphic variation in beads maximum diameter.



Figure S13. Top and centre: fragments of warthog or bushpig tusks from Layer 10 (context 414, spit D) showing scraping marks; bottom: fragment from Layer 7-8 (context 412) showing scraping marks and a deep groove. Scale = 1 mm.



Figure S14. Mesial fragment of a bone point from Layer 9 (context 413, spit C), showing longitudinal scraping (close-up view at the right). Scale = 1 mm.



Figure S15. Notched bone fragments from Layer 9 (context 413, spit A). Scale = 1 mm.



Figure S16. Mesial fragment of a belemnite rostrum from Layer 9 (context 413, spit C), showing traces of abrasion (close-up on the right). Scale = 1 mm.



Figure S17. Iron-rich nodule from Layer 8 (context 104, spit H) presenting a variety of modification traces (see text).

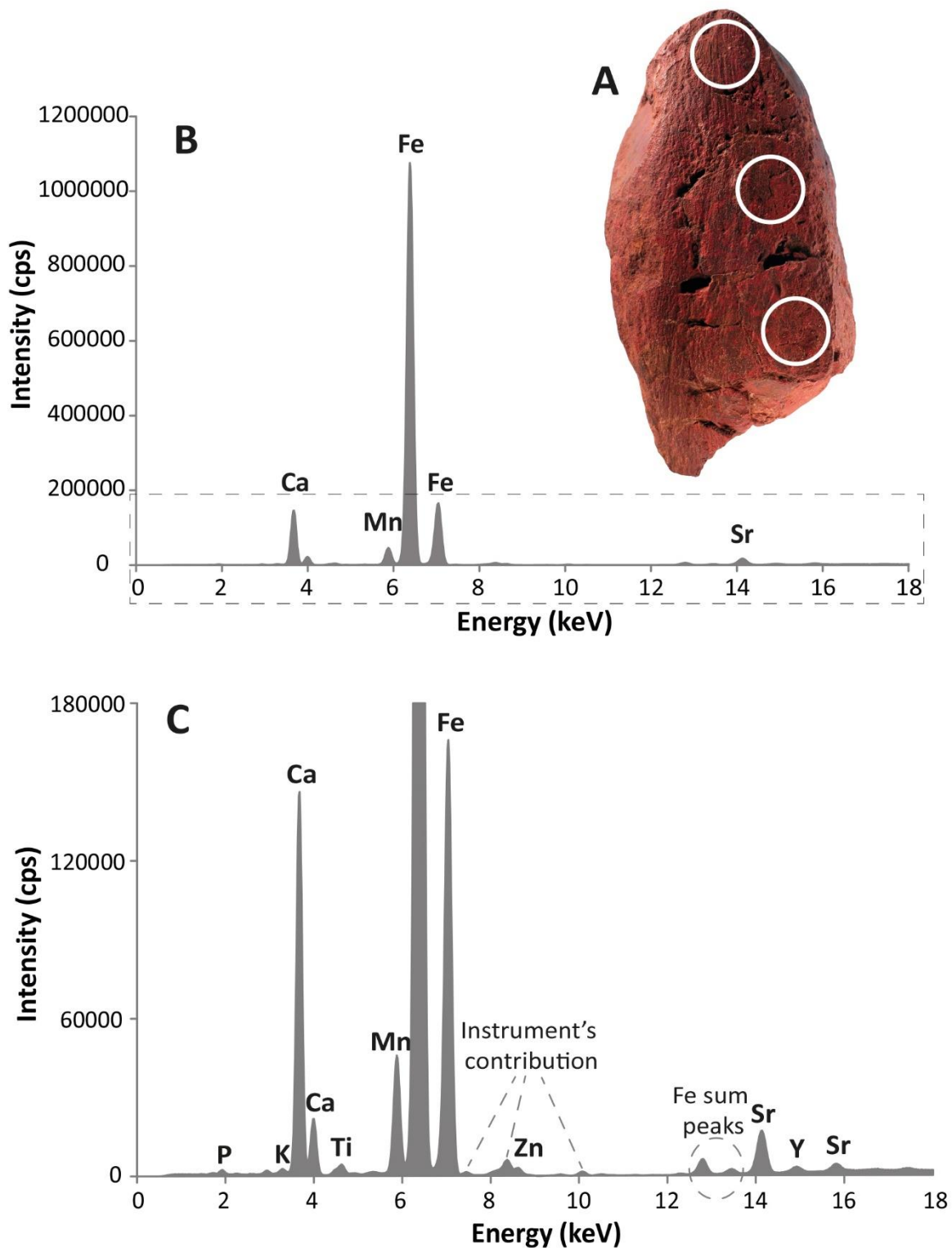


Figure S18. Result of the EDXRF analysis of the Iron-rich nodule from Layer 8 (context 104, spit H) within the specimen from Layer 10, context 313, spit P. A: Location of the analyses. B: EDXRF spectrum. C: Detailed view of the spectrum.

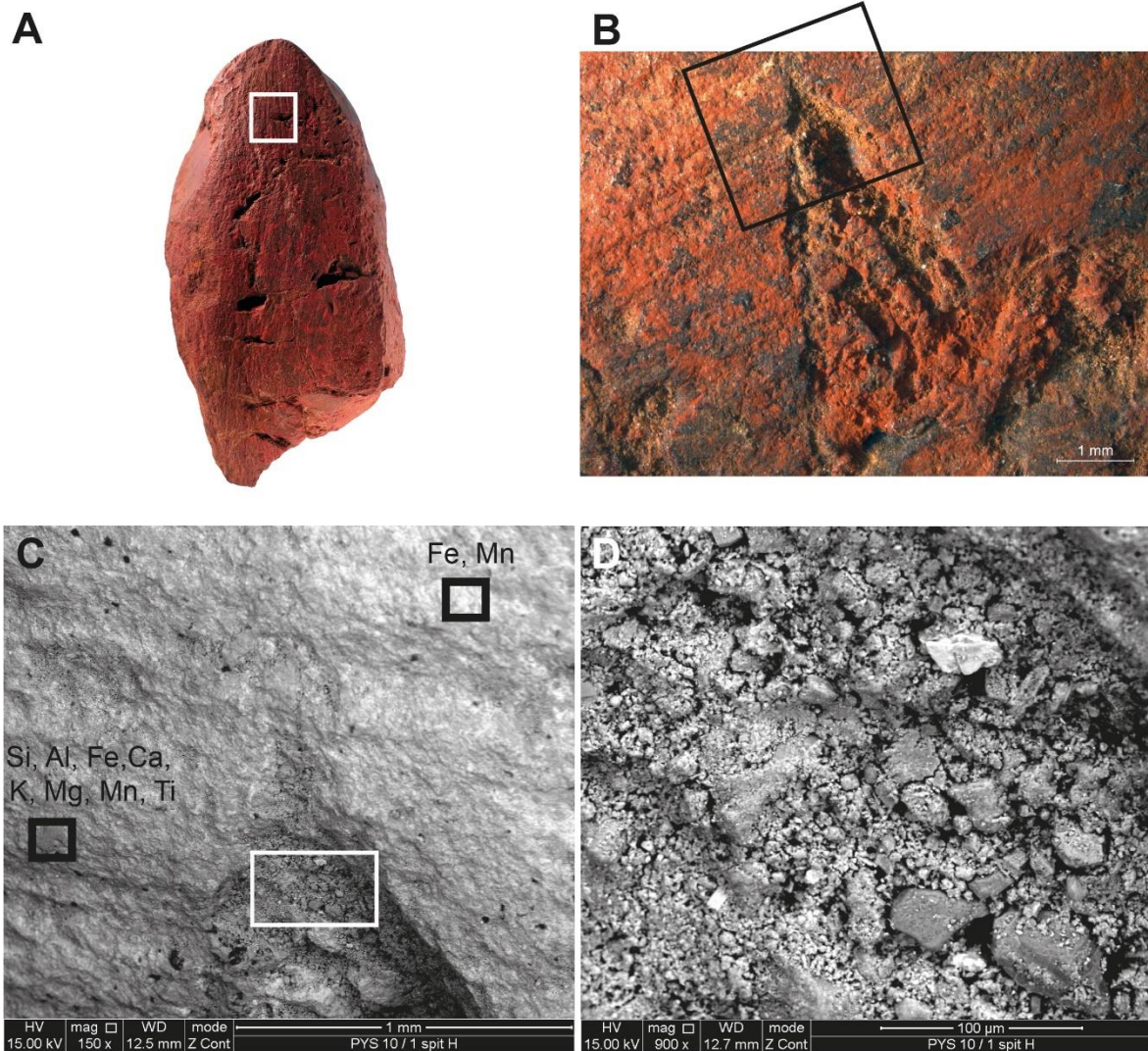


Figure S19. SEM-EDS analysis on the specimen from Layer 8 (context 104, spit H). A-B: Location of the analysis. C: Detailed view of B in BSE mode. D: Detailed view of C.

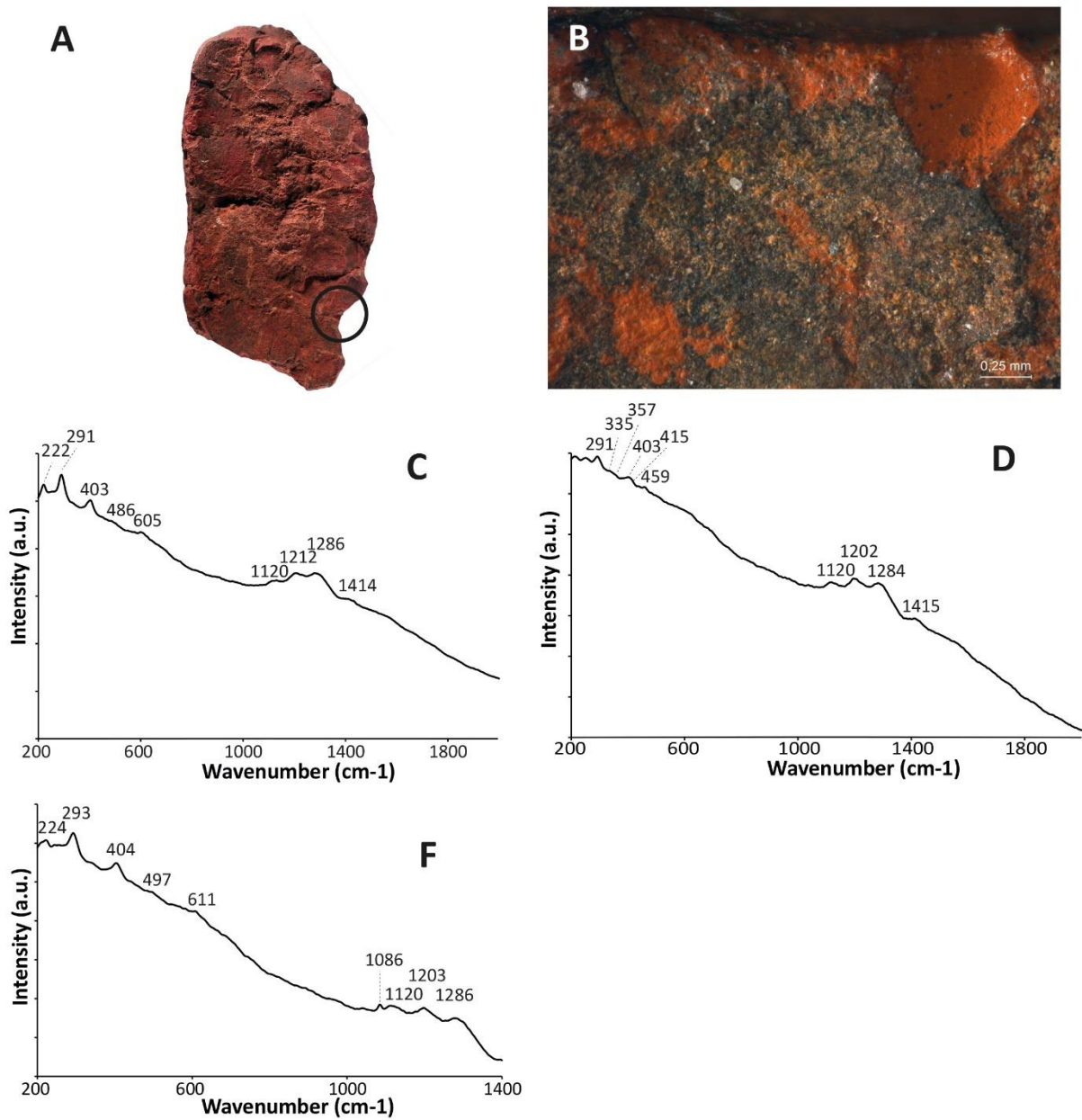


Figure S20. μ -RS analyses on the specimen from Layer 8 (context 104, spit H). A-B: Location of the analyses. C-E: Raman spectra of different sub-areas.



Figure S21. Engraved fragment of ochre from Layer 10 (context 313, spit P).

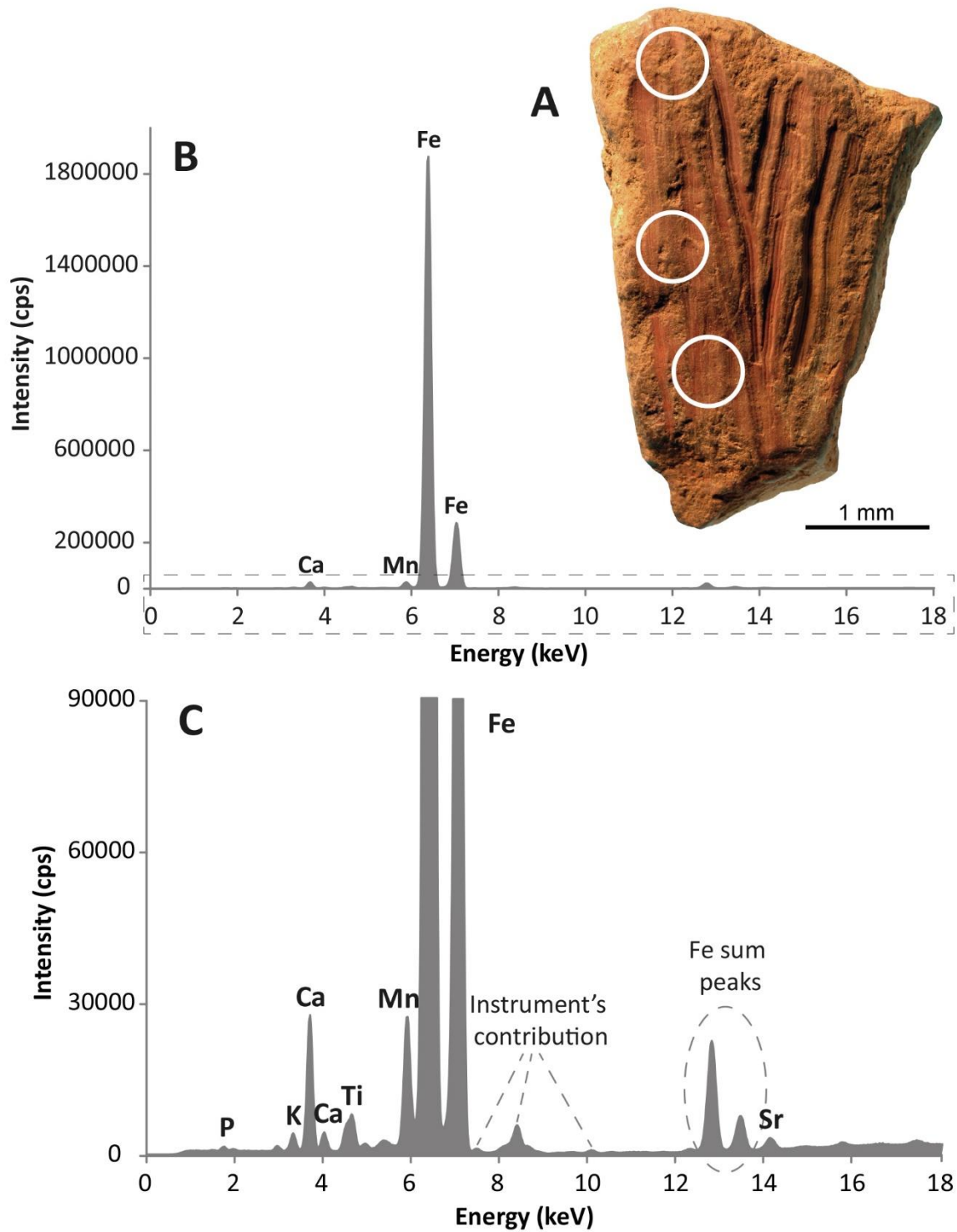


Figure S22. Result of the EDXRF analysis of the engraved fragment of ochre from Llayer 10 (context 313, spit P) within the specimen from Layer 10 (context 313, spit P). A: Location of the analyses. B: EDXRF spectrum. C: Detailed view of the spectrum.

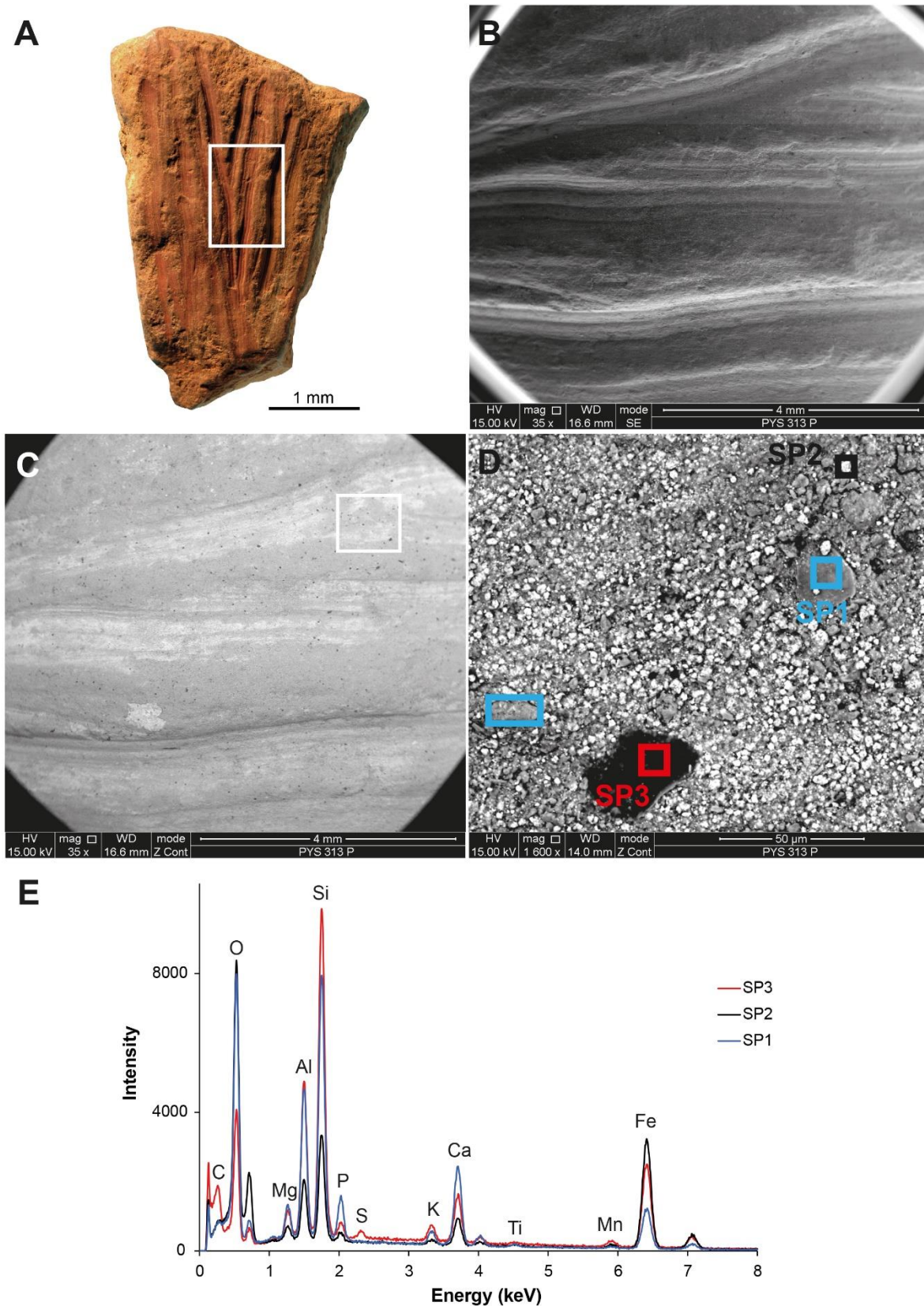


Figure S23. SEM-EDS analysis on the engraved fragment of ochre from Layer 10 (context 313, spit P).

A: Location of the analyses. B-C: SE and BSE mode images at a low magnification. D: Detailed view in BSE mode with the location of the analyzed spots. E: EDS spectra.

A

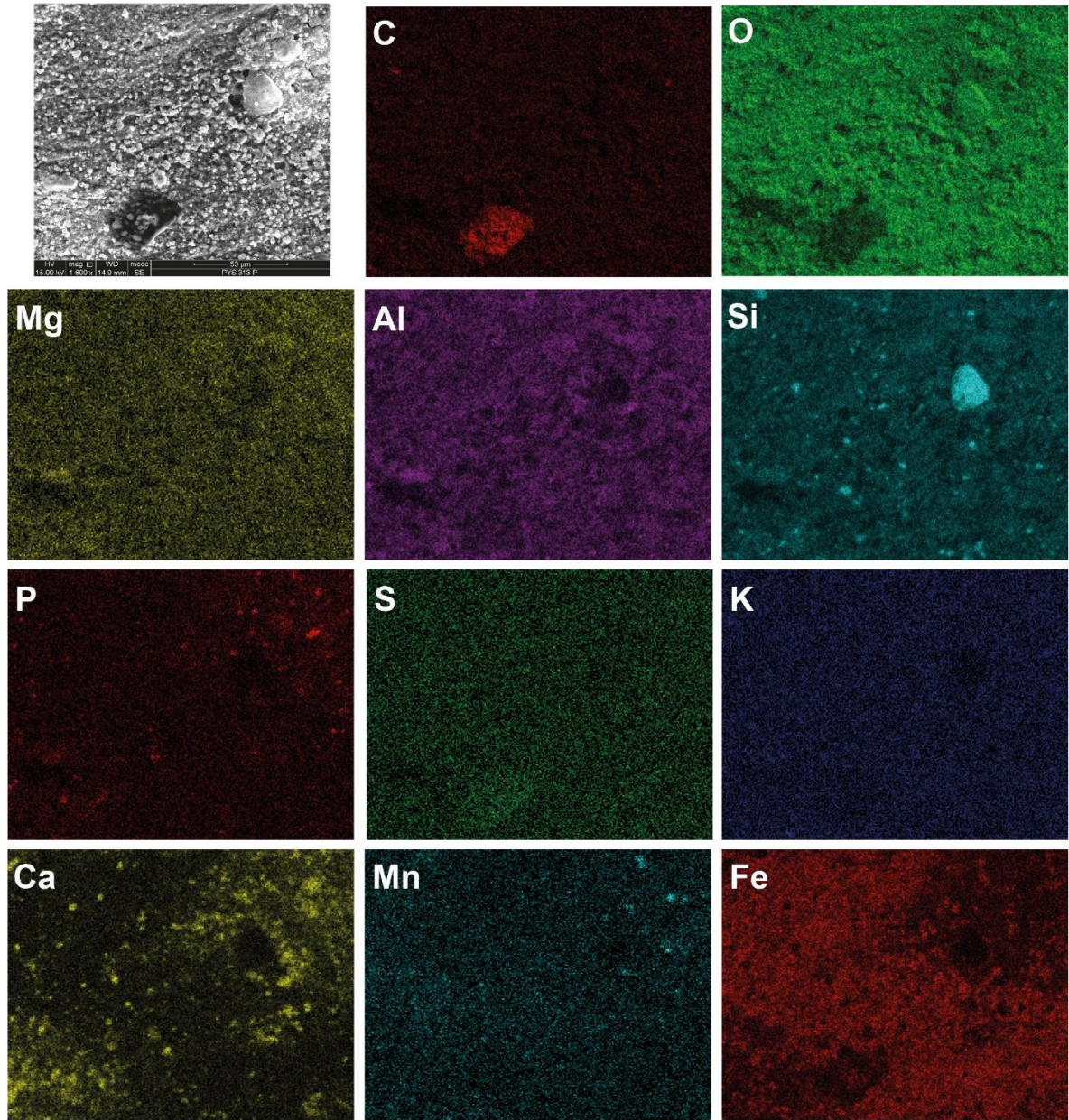


Figure S24. SEM-EDS analysis of the engraved fragment of ochre from Layer 10 (context 313, spit P).
Distribution of the main elements composing the analyzed area.

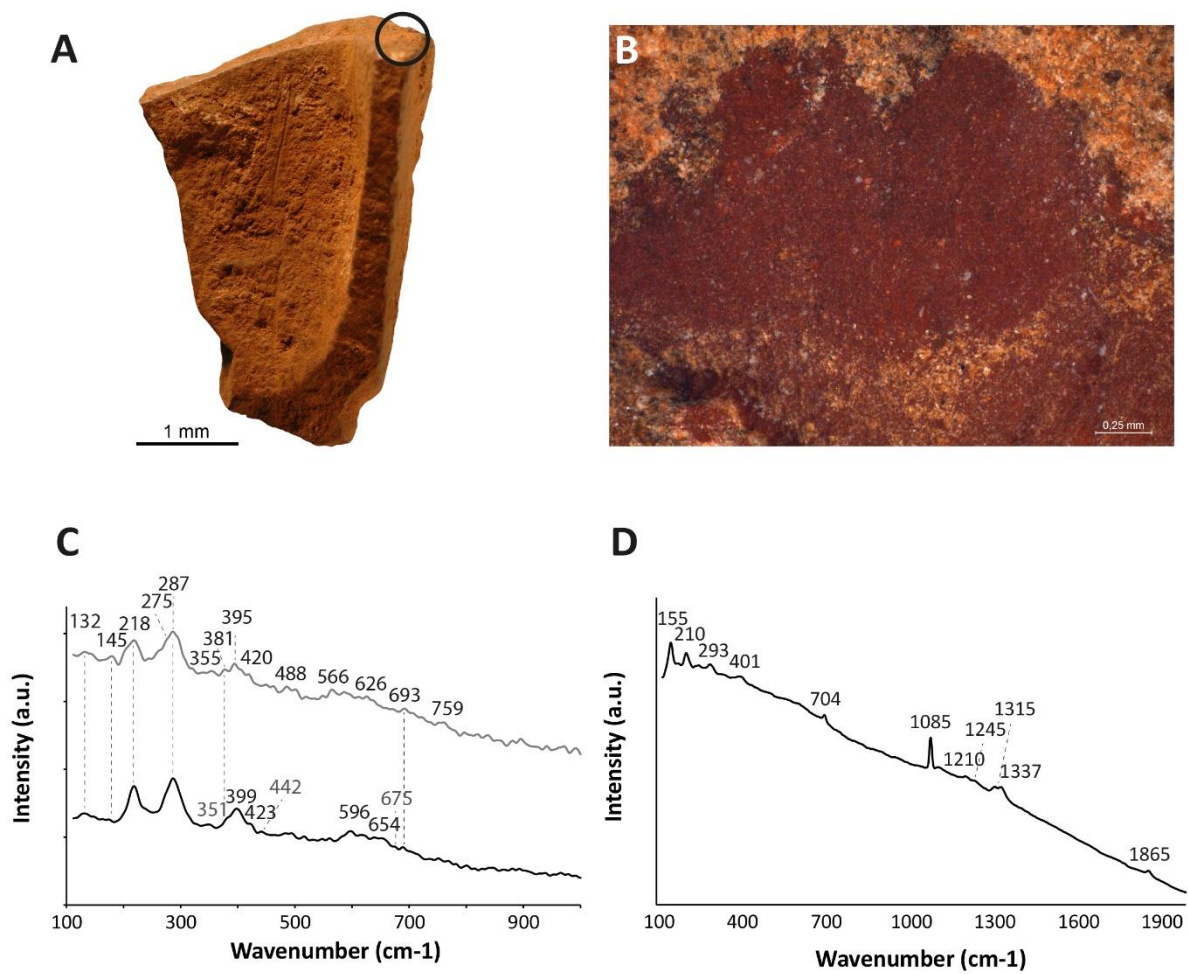


Figure S25. μ -RS analyses on the specimen from Layer 10 (context 313, spit P). A-B: Location of the analyses. C-D: Raman spectra of different compounds.

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innovation in eastern Africa: the case of Panga ya Saidi,
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Supplementary data

S Tables

Table S1. Contextual data and results concerning the pigment analyses.

Table S2. Results of μ -RS analyses on iron-rich lumps from PYS.

Table S3. Results of semi-quantitative SEM-EDS analysis of modified ochre lump PYS-
Layer10-Context 313P.

Table S1. Contextual data and results concerning the pigment analyses						
Unit	Layer	Context or Spit	Sub-sample	Color	Texture	Minerals (μ -RS)
III	7-8	412	a-b	Red	Laminated; clayish matrix with translucent grains (~25-150 μ m); presence of yellow nodules	hem, goe, qtz, cal, gyp
III	8	H (*)		Dark red	Compact clayish matrix	hem, undet. Mn compound, qtz, cal, sil
III	10	313 P (*)		Dark red	Compact clayish matrix	hem, qtz, cal, sil
III	10	414GNRL	b	Dark orange - bright red	Clayish matrix with some quartz grains (~200 μ m) randomly distributed within it; presence of black nodules	qtz, cal (**)
III	10	414D		Pale yellow	Grain-supported fabric composed of subrounded translucent grains (~60-120 μ m) in a clayish matrix	cal, undet. Sil (**)
II	16	420A		Yellow - dark red	Lump of hardened sediment with layers	(***)
I	17	420 F	a	Bright orange	Silty matrix with some angular quartz grains (~200 μ m) scattered on it; presence of vacuoles fulfilled with black deposits	hem, qtz
I	17	420 F	c	Dark orange - bright red	Concretioned silty matrix; grain-supported fabric composed of translucent rounded grains (~400 μ m) and black nodules (~600 μ m)	hem, undet. Mn compound, qtz
I	17	420 F	d	Dark orange - bright red	Concretioned silty matrix; grain-supported fabric composed of translucent rounded grains (~400 μ m) and black nodules (~600 μ m)	
I	17	420 F	e	Dark orange - bright red	Concretioned silty matrix; grain-supported fabric composed of translucent rounded grains (~400 μ m) and black nodules (~600 μ m)	hem, undet. Mn compound, qtz
I	18	422B	a	Dark orange - bright red	Concretioned silty matrix; grain-supported fabric composed of translucent rounded grains (~400 μ m) and black nodules (~600 μ m)	
I	18	422B	b	Dark orange - bright red	Concretioned silty matrix; grain-supported fabric composed of translucent rounded grains (~400 μ m) and black nodules (~600 μ m)	hem, qtz, cal
I	18	422B	d	Dark orange	Concretioned silty matrix containing translucent rounded grains (~200-300 μ m), white crystals (150 μ m), and white nodules; black impregnations are also present	hem, undet. Mn compound, qtz, pho
I	18	422B	e	Dark yellow - bright orange	Silty matrix; matrix-supported fabric; presence of subrounded translucent grains (~350-350 μ m); black impregnations are also present	hem, qtz, fel (**)

hem: hematite; goe: goethite; qtz: quartz; cal: calcite; gyp: gypsum; sil: silicates; pho: phosphates; fel: feldspar; (*) pieces with traces of human modification; (**) too intense fluorescence background; (***) no response

Table S2. Results of μ -RS analyses on iron-rich lumps from Panga ya Saidi

Unit	Layer	Context or Spit	Sub-sample	Item analyzed	Identified minerals	N. meas.
III	8	H		Orange grains	hem (+ sil)	1
III	8	H		Red grains	hem (+ sil)	3
III	8	H		Dark red grains	hem (+ sil)	2
III	8	H		Black grains	undet. Mn compound	2
III	8	H		Translucent white crystals	cal (+ hem + sil)	1
III	8	H		Translucent white grains	qtz (+ hem)	1
III	7-8	412	a-b	Red grains	hem	4
III	7-8	412	a-b	Red grains	hem (+ cal + gyp)	1
III	7-8	412	a-b	Translucent white grains	qtz (+ hem)	2
III	7-8	412	a-b	Translucent white crystals	cal (+ goe + hem + gyp)	2
III	10	313 P		Orange grains	hem	1
III	10	313 P		Red grains	hem	3
III	10	313 P		Dark red grains	hem	3
III	10	313 P		Black grains	hem (+ qtz)	2
III	10	313 P		Translucent white crystals	cal (+ hem + sil)	1
III	10	313 P		Translucent white grains	qtz (+ hem)	2
III	10	414GNRL	b	Translucent white grains	qtz	2
III	10	414GNRL	b	Translucent grey crystals	cal	1
III	10	414D		Translucent grains surrounded by pale yellow particles	cal (+ undet. sil)	4
III	10	414D		Red grains	undet. compound	4
I	17	420 F	a	Red grains	hem (+ qtz)	2
I	17	420 F	c	Red grains	hem	3
I	17	420 F	c	Dark red grains	hem (+ undet. Mn compound)	1
I	17	420 F	c	Black grains	undet. Mn compound	6
I	17	420 F	e	Red grains	hem (+ qtz)	3
I	17	420 F	e	Black grains	undet. Mn compound (+ qtz)	1
I	18	422B	b	Red grains	hem	4
I	18	422B	b	Translucent white crystals	cal	2
I	18	422B	b	Translucent grey grains	qtz	3
I	18	422B	d	Red grains	hem	10
I	18	422B	d	Black grains	undet. Mn compound	4
I	18	422B	d	White particles	pho	1
I	18	422B	d	Translucent white grains	qtz	1
I	18	422B	e	Red grains	undet. compound	4
I	18	422B	e	Red grains	hem (+ alb)	2
I	18	422B	e	Translucent white grains	qtz (+ fel)	2

* in brackets associated minerals; meas: measurements; hem: hematite; sil: silicates; cal: calcite; qtz: quartz; gyp: gypsum; goe: goethite; pho: phosphates; alb: albite; fel: feldspar

Table S3. Results of semi-quantitative SEM-EDS analysis of modified ochre lump PYS-Layer10-Context 313P

Description			Items analyzed	Semi-quantitative EDX analyses **			Interpretation
Grain shape	BSE * contrast	Grain size (µm)		>10%	2-10%	<2%	
Irregular	Black	25	3	(Fe, Al, Si)	C (Ca)	S (Mn, Mg, K, P, Ti)	Undet.
-	Grey	Sub-micrometric	2	Fe, Si	Al, Ca, Mg	K, Mn, Ti (P)	Clay minerals
Rounded grains	Grey	2,5	1	Si (Fe)	(Al, Ca)	(K, Mg, P)	Quartz
Rounded tablets	Grey	20	2	(Fe) Si	(Al, Ca, P, Mg)	(K, Mn, Ti, Na)	Feldspars
Rounded grains	White	2,5	3	Fe	Si, Al, Ca	Mn, Mg, K, P	Hematite

(*): White, Grey, and Black refer to the contrast observed on backscattered electron (BSE) images; (**): Elements in brackets play no role in the mineralogical composition of the analyzed items.