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1 **Evidence for large land snail cooking and consumption at Border Cave c. 170–70 ka ago.**  
2 **Implications for the evolution of human diet and social behaviour.**

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19

20 **Abstract**

21 Fragments of land snail (Achatinidae) shell were found at Border Cave in varying proportions  
22 in all archaeological members, with the exception of the oldest members 5 WA and 6 BS  
23 (>227,000 years ago). They were recovered in relatively high frequencies in Members 4 WA,  
24 4 BS, 1 RGBS and 3 WA. The shell fragments present a range of colours from lustrous beige  
25 to brown and matt grey. The colour variability can occur when shell is heated. This possibility  
26 was explored here through experimental heating of giant land snail shell fragments  
27 (Achatinidae, *Metachatina kraussi* - brown lipped agate snail) in a muffle furnace from 200 to  
28 550°C for different lengths of time. Colour change, weight loss, and shattering of the heated  
29 samples were recorded. Transformation of aragonite into calcite and the occurrence of organic  
30 material was investigated by means of Infrared and Raman spectroscopy. Scanning electron  
31 microscopy was also used on selected specimens to help identify heat-induced transformation  
32 as opposed to taphonomic alteration. The identification on archaeological fragments of  
33 features produced by experimentally heating shells at high temperatures or for long periods  
34 has led us, after discarding alternative hypotheses, to conclude that large African land snails  
35 were systematically brought to the site by humans, roasted and consumed, starting from  
36 170,000 years ago and, more intensively between 160,000 and 70,000 years ago. Border Cave  
37 is at present the earliest known site at which this subsistence strategy is recorded. Previous  
38 research has shown that charred whole rhizomes and fragments of edible *Hypoxis angustifolia*  
39 were also brought to Border Cave to be roasted and shared at the site. Thus, evidence from  
40 both the rhizomes and snails in Border Cave supports an interpretation of members of the  
41 group provisioning others at a home base, which gives us a glimpse into the complex social  
42 life of early *Homo sapiens*.

43

44 *Keywords:* Land snail shell, Infrared and Raman spectroscopy, Scanning Electron  
45 Microscopy, Experimental Archaeology, Broad spectrum revolution

## 47       **1. Introduction**

48       When, how, and why terrestrial molluscs became a constituent part of the diet of our ancestors  
49       are questions that are still largely unanswered and that puzzle researchers in many respects.  
50       Invertebrate animals represent more than 95% of earth's biodiversity (Herbert and Kilburn,  
51       2004), but they are often not studied in archaeological assemblages because they are  
52       considered marginal for the understanding of past human behaviour (Mannino, 2019). In  
53       addition, most of them are small and have little chance of surviving in the archaeological  
54       record. One of the most common remains is from soft bodied animals with mineralised  
55       exoskeletons; molluscs.

56       Land snails may be present in archaeological sites because they occur naturally in the  
57       sediments or because they were introduced by the occupants to consume their flesh and/or to  
58       use their shells as raw materials or as body ornaments (Mannino, 2019). Although the shell  
59       was often used for bead-making in African Iron Age contexts in the late Holocene, older  
60       symbolic use may have occurred too, as evidenced by an *Achatina* shell fragment interpreted  
61       as engraved with a criss-cross pattern, recently found at Txina-Txina, southern Mozambique,  
62       in layers dated 27.4–26.8 ka cal BP (Bicho et al., 2018).

63       Many terrestrial molluscs bury themselves deep in the soil to avoid dehydration during dry  
64       winters (Herbert and Kilburn, 2004), so they can be found naturally in sediments, or they can  
65       be brought to a site by their numerous predators. Adverse climatic events can also cause the  
66       death of snails in their natural habitats and consequently their shells may be incorporated in  
67       cave and shelter deposits through geological processes. Multiple uses of land snail shell have  
68       been investigated from an ethnoarchaeological point of view: including use as tools for  
69       agricultural, fishing, hunting or household purposes, or as decorations or ritual implements

70 (Lubell, 2004a; Mannino, 2019). Snail shells have been discovered in numerous African sites,  
71 including Border Cave, the subject of this volume.

72 At Haua Fteah Cave in Libya, North Africa, preliminary analysis suggests that small land  
73 snails were consumed occasionally from 40–15 ka cal BP, and more regularly from 14–10 ka  
74 cal BP (Barker et al., 2012). The site of Taforalt (Grotte des Pigeons) in Morocco, Northwest  
75 Africa, records land snail consumption from 13–11 ka BP (Taylor et al., 2011). In Beirut in  
76 the Levant the site of Ksar 'Aqil has yielded an accumulation of land snails dated 23–22 ka  
77 BP (Mellars and Tixier, 1989). In Europe, Klissoura Cave 1 in Greece records land snails with  
78 broken lips that are interpreted as evidence of human consumption, in levels dated between 36  
79 and 28 ka cal BP (Kuhn et al., 2010). Nearby, Franchthi Cave documents land snail  
80 consumption between 15 and 12 ka cal BP (Stiner and Munro, 2011). The site of Cova de la  
81 Barriada in Spain preserves compelling evidence for land snail consumption in Europe from  
82 31.3–26.9 ka cal BP (Fernández-López de Pablo et al., 2014). Here land snails were found in  
83 three different levels in association with combustion features, lithic and faunal assemblages.  
84 Charcoal analysis revealed that the snails were roasted in ambers of pine and juniper. X-Ray  
85 diffraction analysis showed that all specimens presented aragonite (CaCO<sub>3</sub>) as the only  
86 mineral phase, indicating that the heating temperature was insufficient to promote the  
87 formation of calcite (Parker et al., 2010). The site of Cueva de Nerja, also in Spain, records  
88 land snails throughout the stratigraphic sequence, including Gravettian (28–19 ka) and  
89 Solutrean (22–17 ka) deposits (Aura Tortosa et al., 2012; Jordá et al., 2011), while the Italian  
90 site of Grotta della Serratura evidences land snail consumption in Epigravettian layers dated  
91 14.1–13.7 ka yrs cal BP (Martini et al., 2009). Edible land snails are often abundant in late  
92 Pleistocene and Holocene archaeological sites, and have been found in the Caribbean, Peru,  
93 parts of North America, East Africa, Sudan, Nigeria, the Philippines and throughout the  
94 Mediterranean region, where they become a substantial part of the human diet (Lubell,

95 2004b). The consumption of land snails continues today in the Mediterranean Basin in Spain,  
96 France, Italy, Portugal, Algeria, Morocco, and Tunisia. Land snails are also consumed in  
97 Nepal, Southeast Asia and Northeast India, and there is a growing demand in South America.  
98 The above review of the evidence highlights, however, what can be perceived as a conundrum  
99 in the history of our lineage's adaptation. Terrestrial molluscs are an excellent source of  
100 nutrients, they are easy and not dangerous to collect, they can be stored for some time before  
101 being consumed, they are simple to prepare and to digest as long as one has a basic mastery of  
102 fire, certainly acquired by hominins at least 400,000 years ago. However, and contrary to  
103 what one might expect, the systematic consumption of terrestrial molluscs does not seem to  
104 date back to before 49 ka in Africa and 36 ka in Europe, and does not become an essential  
105 component of the diet of most human populations before 15–10 ka. Although terrestrial  
106 molluscs, especially those of small dimension, are subject in some sedimentary contexts to  
107 taphonomic processes that can damage or destroy them, it is difficult to attribute the recent  
108 exploitation of terrestrial molluscs to taphonomic causes. For this reason, the dramatic  
109 intrusion of this food source in the late Pleistocene or, depending on the region, early  
110 Holocene, has traditionally been interpreted as a consequence of an expansion of subsistence  
111 resources that would have developed at that time, probably due to demographic pressure. This  
112 “broad spectrum revolution” (Flannery, 1969) would have aimed at the systematic  
113 exploitation of all available resources, and in particular small prey such as small mammals,  
114 fish, reptiles and molluscs (Flannery, 1969; Stiner, 2001; Zeder, 2012). This vision has tended  
115 to attribute possible evidence of older exploitation of terrestrial molluscs to the many natural  
116 phenomena that can lead the remains of these animals to be incorporated into sedimentary  
117 sequences or, at most, to sporadic consumption that does not substantially change the classical  
118 vision of the evolution of the diet of our genus. It is quite possible, however, that this  
119 mainstream narrative reflects only the best-documented and archaeologically visible part of a

120 more complex process that has involved, since the mastery of fire, the exploitation of certain  
121 nutritious species that were only available in certain ecological settings. It is also possible that  
122 these subsistence strategies were lost in some cases and reacquired in others. Because of its  
123 particular characteristics, *Achatina* (giant African land snail) may have been a continuously  
124 exploited species in certain regions of Africa, and may have been an important part of the diet  
125 of Middle Stone Age (MSA) populations long before the "broad spectrum revolution". This  
126 point of view is supported, but not really substantiated, by archaeological evidence that  
127 predates our work at Border Cave. The earliest possible habitual consumption of land snails in  
128 Africa, from Mumba-Höle Cave in Tanzania, East Africa, from level V upper (Lubell,  
129 2004b), dated to  $49.1 \pm 4.3$  ka (Gliganic et al., 2012) consists of *Achatina* sp. shells found in  
130 association with lithic artefacts (Melhman, 1979), though a description of the snail  
131 assemblage is yet to be published. An even older possible consumption of this species comes  
132 from the Kenyan site of Panga Ya Saidi (Martinón Torres et al., 2021). These authors report  
133 large frequencies of *Achatina* sp. fragments, many of which bear traces of heating in the form  
134 of distinct blackening, in layers dated *c.* 78 ka, in which a burial of a three-year-old child was  
135 discovered. More recent evidence for possible MSA exploitation of *Achatina* comes from  
136 Sibudu Cave (Plug, 2004), Bushman Rock Shelter (Badenhorst and Plug, 2012) and Kuumbi  
137 Cave, Zanzibar (Faulkner et al., 2019; Shipton et al., 2016).

138 The Achatinidae family incorporates the largest land snails and KwaZulu-Natal has a  
139 relatively rich agate snail fauna, including 15 species (Herbert and Kilburn, 2004). They are  
140 herbivores, but also consume soil, calcareous rocks, the shells of other molluscs and bone  
141 from carcasses to form their own shells made of the aragonite calcium carbonate ( $\text{CaCO}_3$ )  
142 polymorph (Herbert and Kilburn, 2004). This large gastropod is still a popular food in West  
143 African countries including Cameroon, Ghana and Nigeria (Griveaud, 2016), but not in South  
144 Africa among rural people living in Nkungwini near Border Cave (personal communication

145 by B. Vilane to L.W. in 2016). In some parts of Africa, *Achatina* snails are believed to contain  
146 various curative properties, and the bluish liquid (haemolymph) obtained from the shell  
147 reportedly helps with infant development (Ugwumba et al., 2016; Munywoki, 2022). Snail  
148 meat is highly nutritious; it is rich in protein, iron, potassium, phosphorous, magnesium,  
149 selenium, calcium, copper, sodium, zinc, Omega-3 and other essential fatty acids, and various  
150 vitamins, including vitamin A, Thiamine (B1), Riboflavin (B2), Niacin (B3), vitamin B6,  
151 B12, C, D, E and K, while being low in fat (Aboua, 1990; Fagbuaro et al., 2006). An adult  
152 *Achatina* snail may have a mass of close to a kilogram, so it provides a substantial protein  
153 source. Recent studies (Dumidae et al., 2019) suggest that humans can contract a parasitic  
154 disease caused by a worm hosted by the giant African land snail. Careful handling may  
155 prevent disease. Of course, we do not know whether the parasite is a modern phenomenon or  
156 whether humans in the past were also vulnerable to disease when handling the snails.

157 The objective of this study is to use the results of new high-resolution excavations at Border  
158 Cave and appropriate analytical methods to test the hypothesis that *Achatina* snails were  
159 consumed systematically by human groups in Border Cave between about 170 ka and 70 ka  
160 ago (and occasionally thereafter) and discuss the role that this giant land snail may have  
161 played in early modern human cultural adaptations.

### 162 1.1. *Background to the site*

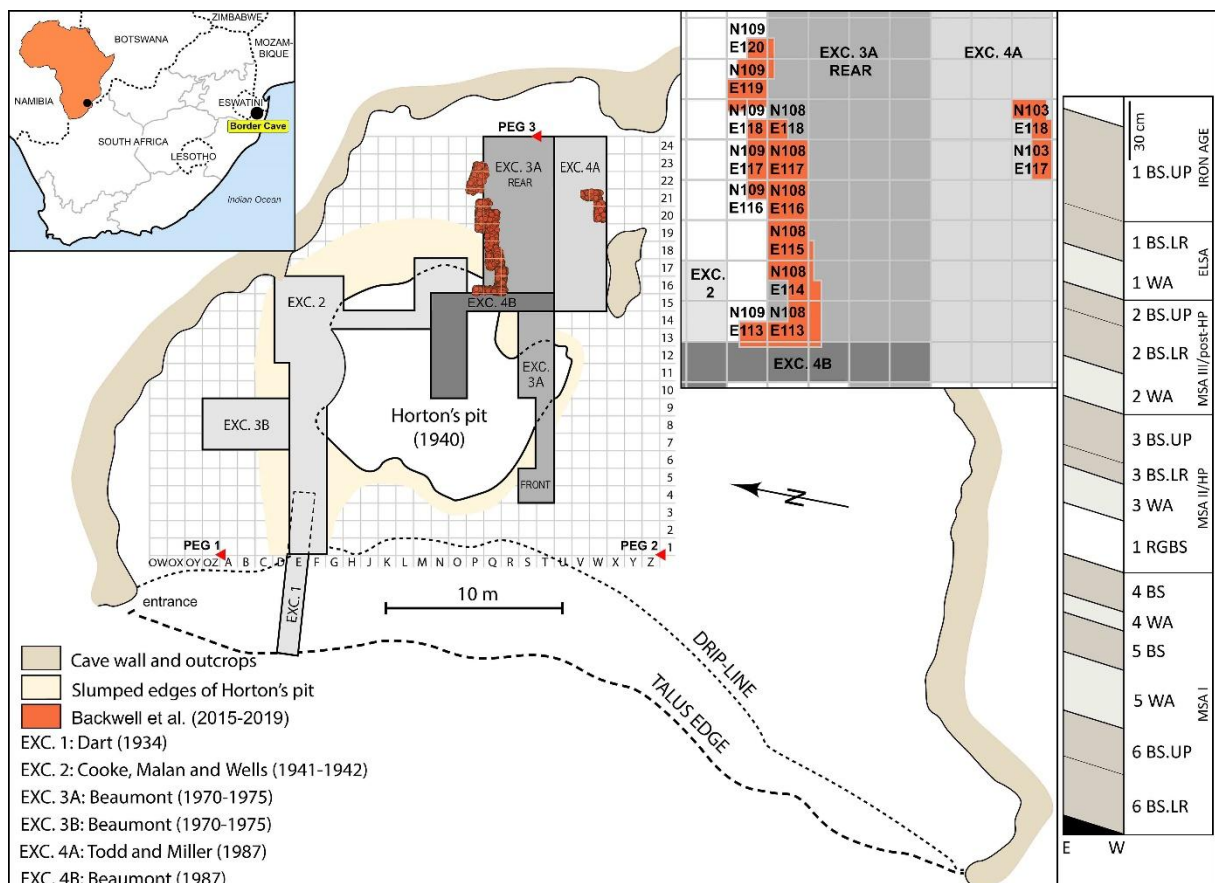
163 Border Cave is located on a cliff, at the border between KwaZulu-Natal in South Africa and  
164 eSwatini (Figure 1). It occurs in the Lebombo mountain range at an elevation of *c.* 600 m  
165 above sea level. The shelter is semi-circular in shape, approximately 50 m wide by 35 m long,  
166 and faces West. The site has been extensively excavated: first, in 1934 by Dart, but his  
167 findings were never published. In 1940 Horton extracted a vast amount of deposit, supposedly  
168 for agricultural purposes, which left a large pit in the middle of the site. The following year



169 Cooke and colleagues resumed archaeological excavations and discovered an infant burial  
170 (BC3) with a *Conus* shell originally covered in ochre (d’Errico and Backwell, 2016), and  
171 recovered additional human remains from Horton’s dump, which they attributed to the Middle  
172 Stone Age (Cooke et al., 1945). Extensive excavations were conducted during the 1970s and  
173 1980s by Beaumont and Todd and Miller (Beaumont, 1978, 1980; Beaumont et al., 1992),  
174 which led to the naming of brown sand (BS) and white ash (WA) members (Figure 1) that  
175 make up the deposit (Butzer et al., 1978), and dating of the stratigraphic sequence (Vogel and  
176 Beaumont, 1972; Beaumont et al., 1978; Beaumont, 1980; Vogel et al., 1986; Beaumont et  
177 al., 1992; Grün and Beaumont, 2001; Grün et al., 2003; Bird et al., 2003; Millard, 2006). In  
178 recent years radiocarbon dating has been applied to archaeological finds (d’Errico et al., 2012;  
179 Villa et al., 2012; Backwell et al., 2018), and now Tribolo and colleagues (this volume)  
180 present optically stimulated luminescence ages for the sedimentary sequence and a suite of  
181 Bayesian model ages for the deposits. Bayesian model ages include all published electron spin  
182 resonance and  $^{14}\text{C}$  ages. Results are given at 2 sigma (95%), and the highest posterior density  
183 is given at 95%. Member 5 WA ranges between ~250–160 ka; Member 5 BS ranges between  
184 ~176–149 ka; Member 4 WA ranges between 167–100; Member 4 BS ranges between ~93–  
185 69 ka; Member 1 RGBS ranges between ~79–67 ka; Member 3 WA ranges between ~74–62  
186 ka; Member 3 BS ranges between ~69–56 ka; Member 2 WA ranges between ~61–53 ka;  
187 Member 2 BS ranges between ~57–43 ka; Member 1 WA ranges between ~45–41 ka and  
188 Member 1 BS ranges between 43–22 ka.

189 The most recent round of excavations started in 2015 under the direction of Backwell, Wadley  
190 and d’Errico (Backwell et al., 2018). Their research has confirmed that the cave records traces  
191 of intermittent occupation from before 227 ka ago until 24 ka, capped by Iron Age occupation  
192 dated to about 600 BP. Their fine-scale approach identifies 10 layers where Beaumont saw  
193 one for Member 1 BS, and 15 in Member 1 WA. They identify 69 layers within his single

194 Member 2 WA and 51 in 4 WA. As opposed to the 10 members identified by Beaumont, 237  
 195 stratigraphic layers have been identified and excavated to date (Backwell et al., this volume;  
 196 Stratford et al., this volume). Beaumont (1978) originally reported remarkable preservation of  
 197 organic remains and the new excavations have confirmed this, with 48 layers of grass  
 198 mats/bedding identified (Sievers et al., this volume). Grass bedding in Member 5 BS dated at  
 199 about 170 ka, and Member 5 WA, dated to >227 ka makes it the oldest known (Wadley et al.,  
 200 2020a; Esteban et al., this volume). The same is true for whole cooked starchy rhizomes,  
 201 identified as *Hypoxis angustifolia*, from layers dated to c. 170 ka ago (Wadley et al., 2020b).  
 202 Charcoal is preserved throughout the sequence, providing a rare and comprehensive record of  
 203 climate change in the region (Lennox et al., this volume). In addition to burning wood for  
 204 cooking, warmth and protection against predators, the charcoal record suggests that plant  
 205 species may have been selected for their latex, nutritional value, insecticidal, medicinal, and  
 206 cosmetic properties (Zwane and Bamford, 2021; Lennox et al. this volume).



207

208 Figure 1. Location of Border Cave and a site plan showing the position of the various  
209 excavations from 1934 to 2019. The orange overlay shows the position of point-plotted  
210 artefacts in excavations conducted from 2015 to 2019 along the North wall of excavation  
211 (EXC.) 3A and South wall of EXC. 4A. The inset (top right) provides the square names  
212 excavated according to North and East lines. Stratigraphic members and associated cultural  
213 attributions after Beaumont et al. (1992) are shown in the column on the right. The alternating  
214 tan and off-white colours denote Brown Sand and White Ash members, and the sloped  
215 dividing lines represent the dip of the deposit.

### 216 1.2. *The Achatina record*

217 During the latest excavations, from 2015 to 2019, shell fragments of giant land snails (Figure  
218 2) were found throughout the sequence, except in the oldest members 5 WA and 6 BS. They  
219 were found in relatively high frequencies in Members 4 WA, 4 BS, 1 RGSB and 3 WA.  
220 Beaumont's extensive excavation of the site yielded 3,529 pieces of *Achatina* shell,  
221 representing a minimum number of 84 individuals (Beaumont, 1978), with the highest  
222 number in Member 4 BS ( $n = 1,076$ ), as is the case with recent excavations (see Backwell et  
223 al., this volume; Figure 7). Backwell and colleagues (this volume) postulate that between  
224 about 170 ka and 70 ka ago land snails may have been a regular part of the diet of visitors to  
225 the cave, and that more recent occupants ate them only occasionally. They acknowledge that  
226 the land snails may have buried themselves in the cave deposit, but consider human  
227 consumption as a more likely explanation for their presence in the deposits because the  
228 *Achatina* shell assemblage is extremely large and mono-specific, the pieces are often  
229 associated with grass mats, combustion features, lithic and faunal remains, and the shells are  
230 fragmented, with a mixture of what they consider to be burned and unburned pieces based on  
231 state of preservation and colour, though the differences may result from non-human  
232 taphonomic processes. The concentrated accumulation of shells in specific stratigraphic units

233 (see Backwell et al., this volume; Figure 7) does not conform to a random distribution of  
234 shells scattered at various depths, as would be the case if the snails had buried themselves in  
235 the deposit.



236

237 Figure 2. Modern Achatinidae land snail. Such agate snails may reach a length of about 160  
238 mm (Herbert and Kilburn, 2004).

239 The fragments vary in colour from lustrous beige to brown and matt grey. Accidental or  
240 deliberate heating of shells is said to account for changes observed in the colour and  
241 chemistry of excavated gastropods (Lange et al., 2006; Bonizzoni et al., 2009; d'Errico et al.,  
242 2015; Milano et al., 2016, 2018). In particular, the shell of *Achatina*, which is essentially  
243 composed of superimposed layers of aragonite, undergoes a mineralogical phase transition  
244 into calcite, associated with morphological changes at microscopic and macroscopic scale, if  
245 the shell is submitted to substantial heating. However, change in colour and chemical  
246 composition can also be produced by non-human taphonomic processes (d'Errico et al.,  
247 2015), and this deserves further enquiry. In order to test the hypothesis that people at Border  
248 Cave cooked and consumed land snails, we used an experimental approach to explore colour  
249 and chemical changes to modern *Metachatina kraussi* shell fragments heated in a muffle

250 furnace at various temperatures and for different lengths of time. The chemical reaction  
251 through heating was studied using vibrational spectroscopy. The macroscopic and  
252 microscopic appearance of the heated shells was documented using photographs, optical and  
253 scanning electron microscopy. The results were compared to a sample of land snail shells  
254 from Border Cave in an attempt to match the features and chemical signatures resulting from  
255 heat, and to establish whether the archaeological specimens might have been similarly  
256 modified.

257

## 258 **2. Material and methods**

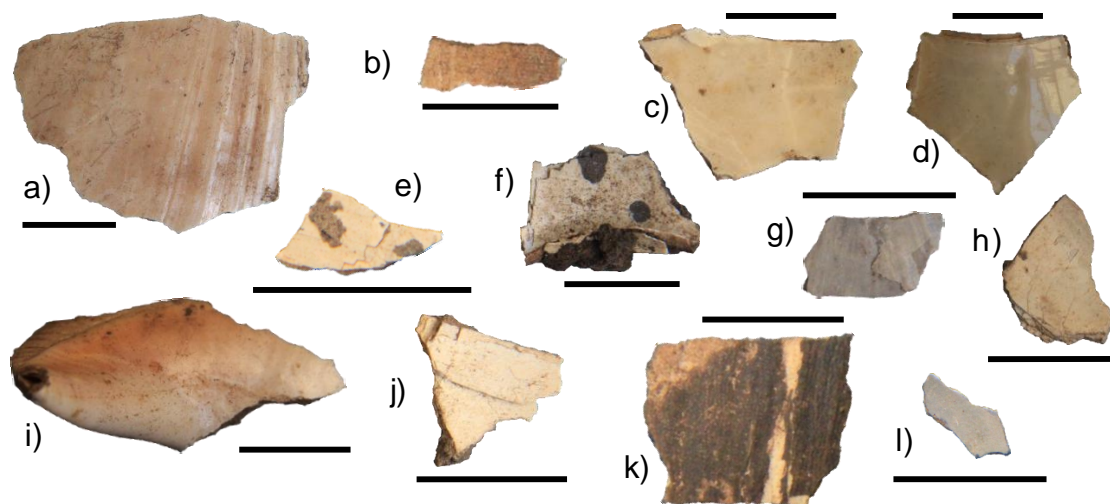
### 259 *2.1. Experimental sample*

260 For the experimental sample, a modern brown-lipped agate snail (Achatinidae, *Metachatina*  
261 *kraussi*) shell from the Verulum region in KwaZulu-Natal was used. It was chosen because it  
262 represents the same family of snails preserved in the archaeological deposits at Border Cave.  
263 The shell ranges in colour from off-white, to beige to brown (Herbert and Kilburn, 2004). It  
264 was broken into multiple pieces using a chunk of rhyolite found on the path leading to Border  
265 Cave. Pieces with many different shapes, sizes and colours were obtained and 41 of them  
266 were selected and used to perform heating experiments. Figure S1 shows photographs of the  
267 giant snail shell before and after crushing as well as the rhyolite used to break it.

### 268 *2.2. Archaeological sample*

269 The archaeological sample studied comes from the recent excavations conducted by Backwell  
270 and colleagues, and more precisely from the 2017 excavation. The shell fragments are  
271 attributed to the Family Achatinidae. The attribution was made based on the relatively large  
272 size of the pieces, their curvature, and pattern made of wavy brown axial lines or stripes. Even

273 though the sample is fragmented, we attribute the shells to *Metachatina kraussi* because of the  
 274 pale wavy axial lines that are distinct from the bold straight ones characteristic of *Achatina*  
 275 *immaculata*, the only other agate snail found in the region (Herbert and Kilburn, 2004). From  
 276 the 87 ziplock bags containing 1,654 shell fragments, 27 pieces showing a range of colours  
 277 and state of preservation were selected for analysis using Raman spectroscopy. Figure 3  
 278 shows photographs of a sample of the selected specimens from Members 4 BS (93.5–69.8 ka)  
 279 and 5 BS (176.8–149.1 ka).



280

281 Figure 3: Examples of Border Cave shell fragments and their stratigraphic context. a) Member  
 282 4 BS, layer Chocolate Brown Ena plan 1; b) Member 4 BS, layer Dark Brown Elmo plan 1  
 283 (Combustion Feature base) sample 3; c) Member 4 BS, layer Chocolate Brown Ena  
 284 (Combustion Feature 1); d) Member 4 BS, layer Chocolate Brown Ena plan 2; e) Member 5  
 285 BS, layer Very Dark Greyish Brown Jim plan 4 (Combustion Feature) sample not selected for  
 286 analysis; f) Member 4 BS, layer Dark Brown Elmo plan 1 (Combustion Feature base) sample  
 287 1; g) Member 5 BS, layer Very Dark Greyish Brown Jan sample 4; h) Member 5 BS, layer  
 288 Very Dark Greyish Brown Jim sample 3 (Combustion Feature); i) Member 4 BS, layer Grass  
 289 mat Ega sample 1 (lip); j) Member 5 BS, layer Very Dark Greyish Brown Jim plan 4  
 290 (Combustion Feature) sample 1 (Combustion Feature base); k) Member 4 BS, layer Dark

291 Grey Eduardo plan 2 (Combustion Feature) sample 2; 1) Member 5 BS, layer Very Dark  
 292 Greyish Brown Jan plan 4 sample 1. All scale bars represent 1 cm.  
 293 Of the 27 samples selected, six specimens did not yield spectra, or the spectra recorded did  
 294 not allow for carbonate polymorph discrimination using the non-invasive Raman analysis and  
 295 these were subjected to invasive (but non-destructive) Infrared analysis. Table 1 lists the  
 296 selected ziplock bags with the number of fragments, their colours, specific features (such as  
 297 the presence of a lip) and the results of the analyses. A preliminary identification of heated  
 298 specimens was based on the sample colour and state (cracks, if it was brittle, etc.) The full  
 299 table of samples from the 2017 excavation can be found in Table S1.

300 **Table 1.** List of archaeological shell fragments excavated in 2017 and selected for the  
 301 analysis. Each line refers to a ziplock bag, from which one to four specimens were selected  
 302 for study. Cultural attributions according to Beaumont et al. (1992). ATR-FTIR: Attenuated  
 303 Total Reflectance Fourier Transform Infrared Spectroscopy; AC: amorphous carbon; BS:  
 304 brown sand; CF: combustion feature; MnOx: manganese oxide; Orga: organic matter; WA:  
 305 white ash; ELSA: Early Later Stone Age.

Cultural attribution	Member	Layer	Plan	Number of fragments	Colour	Signs of heating	Note/Samples selected	Raman	ATR-FTIR
ELSA	1 WA	Grass Mat Betty	1	1	beige	possibly	Lip	Calcite	-
MSA III	2 WA	Very Dark Brown Dax	1	1	beige	possibly	-	Fluorescence	Bone (Apatite)
MSA II	1 RGBS	Very Dark Brown Eba	2	2	grey	possibly	Sample 1	Calcite, AC	-
							Sample 2	Calcite, Gypsum	-
MSA I	4 BS	Dark Grey Eduardo (CF)	2	15	beige	possibly	Sample 1	Aragonite, MnOx, Gypsum	-
							Sample 2	Aragonite, AC	-
							Sample 3	Aragonite	-
	4 BS	Dark Grey Eduardo	2	3	1 grey, 2 beige	possibly	Sample 1 (beige)	Aragonite	-
							Sample 2 (grey)	Calcite, AC	-
							Sample 3 (beige)	Aragonite	-

	4 BS	Grass Mat Ega	1	2	beige	no	-	Aragonite	Aragonite, Orga, Apatite, silicates
	4 BS	Grass Mat Ega	1	1	beige/brown	possibly	Lip	Aragonite, Carotenoid	Aragonite, Orga, Apatite, Silicates
	4 BS	Dark Brown Elmo (CF base)	1	19	10 grey, 9 beige	possibly	Sample 1 (grey/black)	Aragonite, Calcite, MnOx, AC	-
Sample 2 (grey)							Calcite, AC	-	
Sample 3 (beige)							Aragonite	-	
	4 BS	Chocolate Brown Ena	1	1	beige	no	Scratches, striations on the outer part, shiney both sides	Aragonite	-
	4 BS	Chocolate Brown Ena (CF1)	1	1	beige	no	Cracks visible macroscopically on the inner part	Aragonite, AC	-
	5 BS	Very Dark Greyish Brown	?	1	beige	possibly	-	Aragonite	-
	5 BS	Very Dark Greyish Brown Jan	1	1	grey	?	-	Calcite	-
	5 BS	Very Dark Greyish Brown Jan (CF1)	3	1	beige	possibly	-	Carbonate	Calcite, Silicates (sediments)
	5 BS	Very Dark Greyish Brown Jan	4	2	grey	possibly	Sample 1	Bone	-
							Sample 2	Calcite, AC	-
	5 BS	Very Dark Greyish Brown Jim (CF)	3	1	beige	possibly	-	Calcite	-
	5 BS	Very Dark Greyish Brown Jim (CF)	4	6	2 grey, 4 beige	possibly	Sample 1 (beige)	Carbonate	Calcite, Silicates, Gypsum
							Sample 2 (grey)	Calcite, AC	-
							Sample 3 (grey)	Fluorescence	Bone (Apatite), Gypsum
							Sample 4 (beige)	Aragonite	-

306

### 307 2.3. Heating experiments

308 Three experiments were performed with a muffle furnace. The temperature varied from 200 to

309 550°C and the heating time from 5 minutes to 36 hours. The first experiment was performed



310 to determine at which temperature the mineralogical transformation from aragonite to calcite  
311 and colour change start when heated for a short period of time (5 minutes) from 200°C to  
312 550°C with a 50°C increment. For each temperature step three fragments of different colour  
313 were used. The fragments also exhibited different thicknesses, which can also influence the  
314 transformation. The second experiment explored heat exposure for an increased period of time  
315 (20 minutes) starting from 300°C (since the lower temperatures showed limited change during  
316 the first experiment) to 550°C. Two fragments per temperature step were heated to check  
317 reproducibility. The last experiment focused on heat exposure time at a set temperature  
318 (350°C) ranging from 1 hour to 36 hours. The rationale being that if archaeological fragments  
319 of shell were present around a fire, they could have been exposed to heat for long periods of  
320 time. The fragments were inserted when the furnace reached the desired temperature.  
321 Different shell fragments were used depending on their colour (white, beige, or brown) and  
322 some of them were cleaned with water and a soft brush to clearly see the colour change of the  
323 shell. Not all were cleaned since shell was unlikely to have been cleaned in the past. The  
324 weight loss, established at a precision of 0.001g, and the colour change were recorded, and the  
325 specimens were photographed before and after heating. Table 2 lists the different experiments  
326 (temperature, duration, initial colour and if the sample was cleaned or not) with their  
327 respective results (colour and appearance after heating, weight loss, if the sample shattered or  
328 not and the Raman and FTIR results).

329 **Table 2.** List of heating experiments in terms of parameters and results. ATR-FTIR:  
330 Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy; AC: amorphous  
331 carbon; bh: before heating; ah: after heating; MnOx: manganese oxide; Orga: organic matter;  
332 N: no; Y: yes; ?: indeterminate compound; min: minutes; h: hours. The weight loss could not  
333 be measured for the samples which shattered (since many fragments were scattered).

Temperature (°C)	Heating time	Sample colour bh	Cleaned	Sample colour & appearance ah	Weight loss (%)	Shattered	Raman	ATR-FTIR
200	5 min	white	x	white	0.00	N	Aragonite, Carotenoid	Aragonite
		beige		beige	0.13	N	Aragonite	Aragonite, Orga
		brown		brown	0.12	N	Aragonite, Carotenoid, ?	Aragonite, Orga
250		white		white	0.47	N	Aragonite, Carotenoid, AC, Feldspar, Romanéchite	Aragonite
		beige		beige	0.07	N	Aragonite, Carotenoid, AC, ?	Aragonite, Orga
		brown		light brown	0.27	N	Aragonite, Carotenoid	Aragonite, Orga
300		white		white	0.50	N	Aragonite, Haematite	Aragonite
		beige		beige	0.28	N	Aragonite, AC	Aragonite, Orga
		brown		light brown	0.28	N	Aragonite, Carotenoid, AC	Aragonite, Orga
350		white		white with darkening of brown areas	0.47	N	Aragonite, AC	Aragonite
		beige		beige with darkening of brown areas	0.70	N	Aragonite, AC	Aragonite, Orga
		brown		brown became grey & darkening of brown areas	0.46	N	Aragonite	Aragonite, Orga
400		white		white	0.43	N	Aragonite, AC	Aragonite
		beige (a bit of brown)		beige & brown became black	0.49	N	Aragonite, AC, ?	Aragonite, Orga
		brown		brown became beige & is black on some areas	0.47	N	Aragonite, AC, ?	Aragonite, Orga
450		white		white	0.51	N	Aragonite, AC, ?	Aragonite
		beige		white (darkening on some areas)	0.83	N	Aragonite, AC, ?	Aragonite, Orga
		brown		white	0.73	N	Aragonite, AC	Aragonite, Orga
500	white	whiter	1.49	N	Aragonite, Calcite, AC, MnOx, Anatase	Calcite, Aragonite		
	beige (a bit of brown)	white (brown became black)	-	Y	Aragonite, Calcite, AC, Haematite, ?	Calcite		
	brown	white (brown became black)	-	Y	Aragonite, Calcite, AC	Calcite, Aragonite		
550	white	whiter	-	Y	Calcite	Calcite		
	beige	white (bit of brown left)	-	Y	Aragonite, Calcite	Calcite, Aragonite		
	brown	white/grey	-	Y	Aragonite, Calcite, AC	Calcite, Aragonite		
300	20 min	beige	x	darker outside, whiter inside	0.00	N	Aragonite, AC,	Aragonite

							Maghemite	
		beige/brown & green spots	-	darker & green became brown	0.00	N	Aragonite, AC, MnOx	Aragonite, Orga
350		beige (a bit of brown)	x	whiter, brown became black	0.35	N	Aragonite, Carotenoid, AC, ?	Aragonite
		white & green spots	-	whiter, green became black/brown	0.53	N	Aragonite, AC, ?	Aragonite, Orga
400		white	x	whiter	0.21	N	Aragonite, AC, ?	Aragonite, Calcite
		white/brown	-	whiter, brown became black	0.31	N	Aragonite, AC, ?	Aragonite, Orga
450		beige	x	very white, separation of layers (at least 3 layers)	1.43	N	Aragonite, MnOx	Calcite
		beige/brown	-	white, brown became black, layer separation (at least 4)	1.29	N	Aragonite, Calcite, AC	Calcite, Aragonite
500		white	x	whiter, layer separation & cracking	1.90	N	Aragonite, Calcite, MnOx	Calcite, Aragonite
		beige/brown	-	white, slightly grey outside, layer separation, cracking	1.63	N	Calcite, MnOx, Maghemite	Calcite + Aragonite
550		white	x	grey/white	1.22	N	Calcite, MnOx	Calcite, Aragonite
		white	-	grey/white	-	Y	Calcite, AC	Calcite, Aragonite
350	1 h	beige/brown	-	whiter, brown became black	0.49	Y	Aragonite, AC, MnOx, ?	Aragonite, Orga
	3 h	beige/white	-	beige/whiter, outer layer detached from the inner ones	1.35	N	Aragonite, AC, Haematite, Quartz, Anatase	Aragonite, Orga
	6 h	beige/brown	-	whiter, brown became black	1.40	Y	Aragonite, AC, Anatase, ?	Aragonite, Calcite
	12 h	beige/brown	-	very white inner part, sample broke & layers bent in opposite directions	1.04	N	Aragonite, Calcite, AC	Aragonite, Calcite
	36 h	beige/brown	-	disappearance of many brown areas, the colour became matt, cracks, outer layer detached from the inner ones	1.19	N	Calcite, AC, MnOx	Aragonite, Calcite

334

335 2.4. Optical microscopy

336 Optical microscopic observations were conducted using an Olympus BX63 upright  
337 microscope with reflected light and CellSem Dimension software. The z-stacking option of  
338 the software was used with magnification objectives of 4× and 10×.

### 339 *2.5. Raman micro-spectroscopy*

340 Raman spectroscopy can help to determine the molecular composition of the samples. Here,  
341 all experimental samples (n = 45) and archaeological specimens (n = 27) were analysed on  
342 both sides, on multiple spots with a green laser covering a very localised surface area of  
343 around 1 µm. Raman spectra were recorded using a LabRam HR 800 spectrometer (Horiba  
344 Jobin–Yvon), with a 514.5 nm line of a Lexel argon ion laser, equipped with an Olympus  
345 BX41 microscope attachment. A charge coupled detector cooled with liquid nitrogen  
346 collected the spectra with a spectral resolution  $<2\text{ cm}^{-1}$  using the 600 lines/mm grating. The  
347 spectrometer was set to save the 80–1,800  $\text{cm}^{-1}$  spectral range, and the laser beam power  
348 directed at the sample was kept under 0.8 mW to avoid inducing thermal transformation. The  
349 spectra were acquired with a 100x long working distance giving a spatial resolution of around  
350 1 µm for 8 to 350 seconds, repeated at least twice.

### 351 *2.6. Infrared spectroscopy*

352 Fourier Transform Infrared spectroscopy (FTIR) was performed with a Bruker Alpha  
353 spectrometer equipped with an Attenuated Total Reflectance (ATR) module. A small piece  
354 (few millimetres wide) of the selected specimen was broken and finely ground in an agate  
355 mortar to obtain a homogeneous and fine powder that was pressed onto the diamond crystal.  
356 Spectra were acquired in the mid-IR range between 400 and 4,000  $\text{cm}^{-1}$  (Deuterated  
357 TriGlycine Sulfate detector) with 64 scans and a 4  $\text{cm}^{-1}$  resolution. An atmospheric  
358 compensation was applied to the spectra using OPUS 7.5 software.

### 359 *2.7. Scanning electron microscopy*

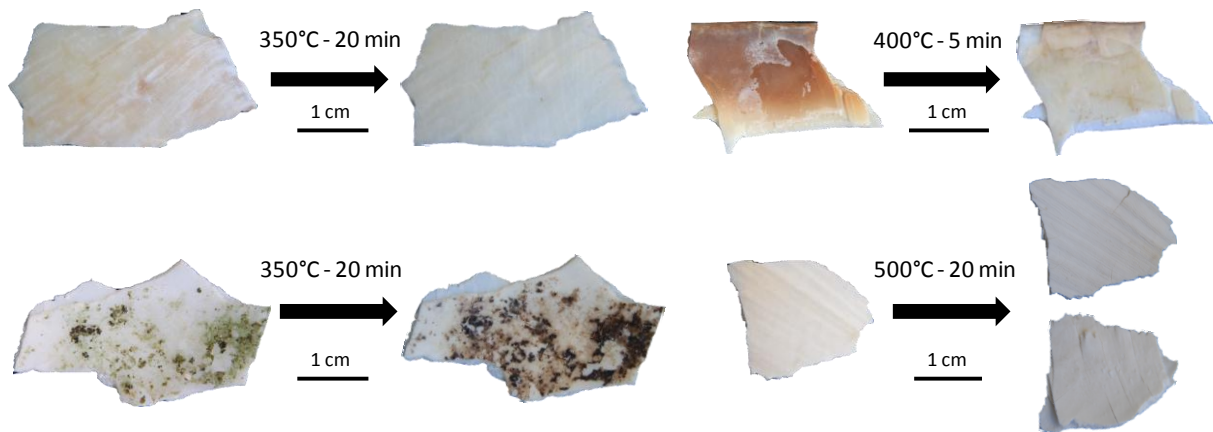
360 Scanning electron microscope (SEM) observations were made and images captured with a  
361 Phenom Pure generation 5 instrument from Thermo Fisher Scientific. The samples were  
362 placed on adhesive carbon tape. The backscattered images were acquired at a working  
363 distance of ~10 mm at 5 kV. SEM observations were performed on the inner and outer parts  
364 of a white experimental control specimen not heated, a grey piece heated at 500°C for 20  
365 minutes, and on the inner part of three archaeological samples with different compositions.  
366 These samples are a beige sample composed of aragonite from Member 5 BS, layer Very  
367 Dark Greyish Brown Jan, not showing any signs of heating macroscopically (accession  
368 number 3038), another beige sample from Member 5 BS (accession number 5256) composed  
369 of calcite and thus likely heated, and sample 1 (grey/black) from Member 4 BS, layer Dark  
370 Brown Elmo (combustion feature base) exhibiting a mixture of calcite and aragonite.

### 371 **3. Results**

#### 372 *3.1. Experimental heating and macroscopic observations*

373 The weight loss for samples heated at the lower temperature (200 to 300°C) and for a short  
374 period of time oscillated around 0.5% that likely corresponds to the loss of water. For samples  
375 heated for longer periods and at higher temperatures, the weight loss was around 1 to 2 % and  
376 probably entailed the entire or partial loss of organic matter (Table 2). In the case of land  
377 snails, the carbonate crystals that constitute the shell are bound in an organic framework of  
378 tanned proteins that protect the shell against humic acids present in the soil (Herbert and  
379 Kilburn 2004). Starting from 450°C, some samples shattered and/or there was a separation of  
380 the different layers comprising the shell (Figure S2). The effect of heat on colour was that the  
381 originally white specimens became a more snow white, while the beige and brown samples  
382 lost their colour (Table 2, Figure 4). Starting from 500°C for at least 20 minutes, the samples  
383 turned grey. After heating, most of the specimens lost their initial gloss and became matt. This

384 is because the organic matter present in the shell structure is responsible for the glossy  
385 appearance (Nouet, 2014). Hence, the loss of gloss corresponds with the loss of organic  
386 matter, as confirmed by vibrational spectroscopy, which did not detect organic matter in matt  
387 samples.



388

389 **Figure 4.** Representative colour change of the experimental *Metachatina kraussi* shell  
390 fragments through heating. The top left specimen was cleaned and considered as beige before  
391 heating. The bottom left specimen was not cleaned, and the adhering organic matter turned  
392 black and stained the shell pale brown. The top right specimen was considered brown before  
393 heating and lost its colour, and the bottom right specimen was white before heating and turned  
394 matt grey.

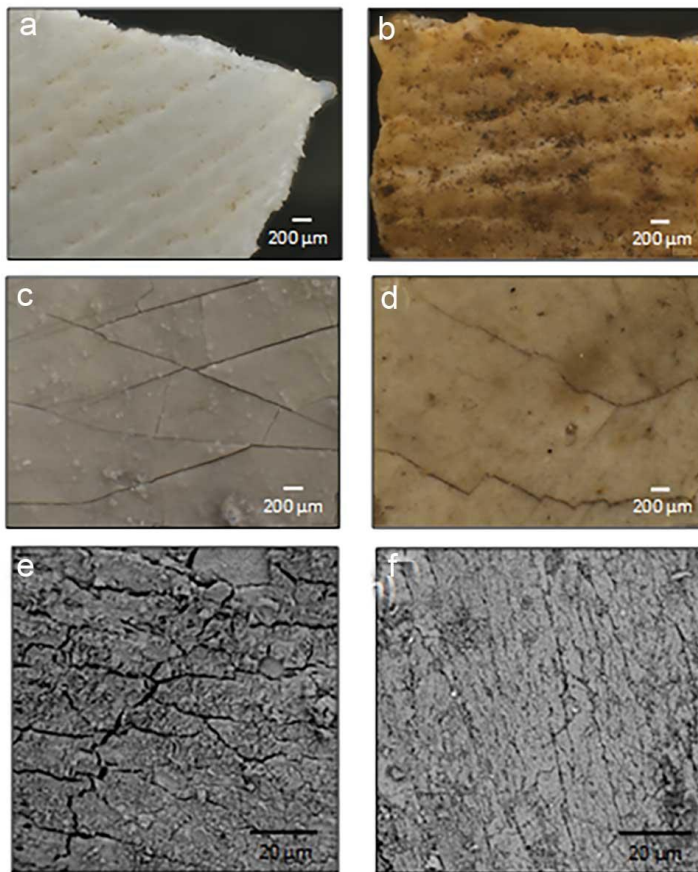
395 Of the 1,654 archaeological fragments unearthed in 2017, 82.6 % exhibit a beige colour,  
396 15.3 % are grey, 1.9 % brown and only 0.2 % are black (Table S1 and Figure 3). Several  
397 samples show some black staining which could be due to manganese oxides and many display  
398 cracks. Some of the beige specimens appear very glossy, while others are matt. The grey,  
399 brown, and black ones are always matt. The loss of organic matter that makes shell appear  
400 glossy may be attributed to heat, although microbial attack of organic matter and diagenesis  
401 could also be possible causes.

### 402 3.2. *Microscopic observations*

403 At a microscopic scale it is possible to observe in detail the ridges present on the in- and  
404 outside of the modern shell fragments (Figure 4a). These correspond to the successive growth  
405 increments of the shell (Nouet, 2014). The same growth ridges are clearly visible on the  
406 archaeological specimens (Figure 4b) and they help to confirm our identification of the snail  
407 shell. Cracks can be observed on the modern heated specimens, which also lack gloss and  
408 have a matt surface (Figure 5c). The same features are observed on the archaeological  
409 specimens, which are similarly cracked with a matt surface (Figure 5d). Scanning electron  
410 microscope analysis of modern heated shells reveals a plethora of desiccation cracks resulting  
411 from rapid water loss (Figure 5e). Similar microscopic cracking of the surface was observed  
412 on archaeological specimen (Figure 5f). SEM also revealed fusion of a shell's original  
413 microstructure after it was heated at high temperatures such as 500 to 700°C (Milano et al.  
414 2016, 2018). Other taphonomic processes caused by localised dissolution, fusion and  
415 recrystallization processes can also be observed with SEM (Toffolo, 2021) but were not  
416 observed on the Border Cave specimens.

417 Microscopic analysis of the modern heated shells and archaeological specimens from Border  
418 Cave shows that they share features resulting from exposure to heat, namely micro-cracking  
419 and a matt surface appearance. This finding, and the fact that most of the archaeological  
420 specimens derive from combustion features (see Table 1) demonstrates that these shell  
421 fragments were most likely heated.

422



423

424 **Figure 5.** Microscopic images of modern (left) and archaeological (right) land snail shells. a)  
 425 Growth ridges on a modern unmodified shell fragment, and b) similar growth ridges on an  
 426 archaeological specimen from Member 3 BS, layer Dark Brown Elmo, plan 1 combustion  
 427 feature base. c) Cracks observed on a cleaned modern shell fragment heated at 550°C for 20  
 428 minutes, and d) similar irregular cracks recorded on an archaeological specimen from  
 429 Member 5 BS, layer Very Dark Greyish Brown Jim, plan 3 (combustion feature). e)  
 430 Uncleaned modern shell fragment heated at 500°C for 20 minutes showing extreme micro-  
 431 cracking of the desiccated surface, and f) archaeological specimen from Member 5 BS, layer  
 432 Very Dark Greyish Brown Jim, plan 3 (combustion feature - accession number 5256) showing  
 433 similar fine cracking over the entire surface of the piece. Scales in a-d = 200 μm; scales in e, f  
 434 = 20 μm.

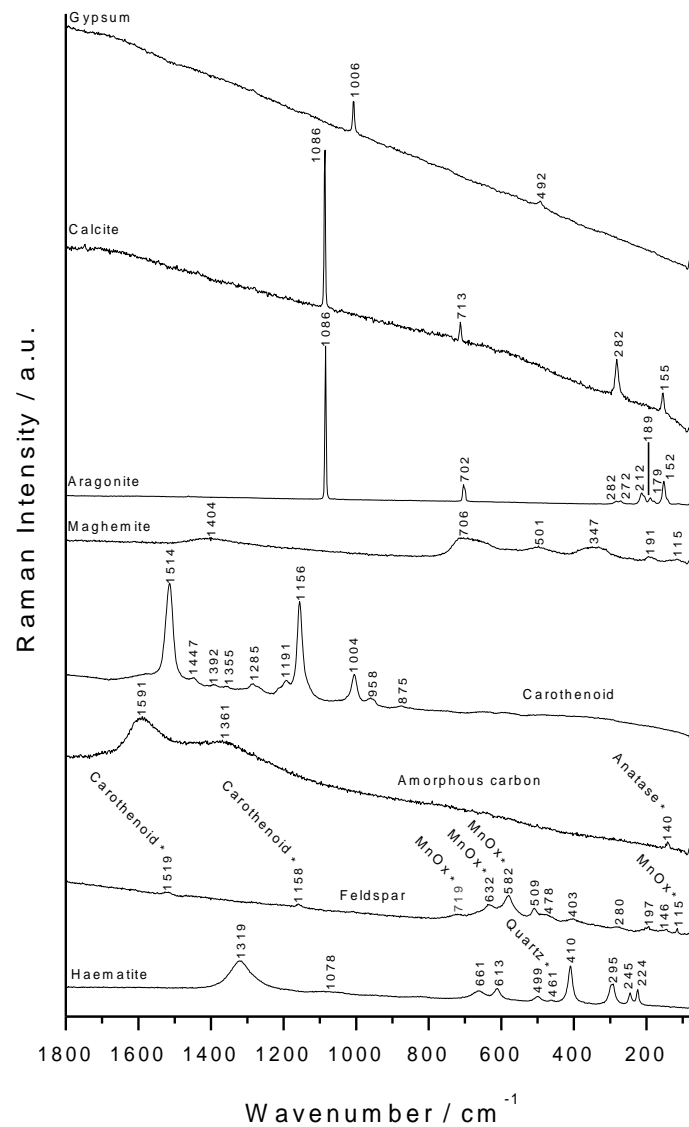
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### 436 3.3. Raman micro-spectroscopy

437 The spectra of compounds detected on the experimental and archaeological specimens are  
438 presented in Figure 6, and Tables 1 and 2 list the compounds obtained for each specimen  
439 analysed. Before heating, only the calcium carbonate polymorph of aragonite was detected on  
440 the fragments of the brown-lipped agate snail shell (Table 2). It is one of the polymorphs of  
441 calcium carbonate ( $\text{CaCO}_3$ ) with characteristic Raman peaks located around 152, 179, 189,  
442 212, 272, 282, 702 and  $1086 \text{ cm}^{-1}$  (Urmos et al., 1991). On the brown parts of the shell  
443 fragments before heating, carotenoids were identified with vibrational bands located around  
444 875, 958, 1004, 1156, 1191, 1285, 1355, 1392, 1447 and  $1514 \text{ cm}^{-1}$  (Maguregui et al., 2012).  
445 Spectra of amorphous carbon, quartz, haematite, maghemite, feldspar and manganese oxides  
446 (Mernagh, 1991; Chamritski and Burns, 2005; Prinsloo et al., 2013; Bernardini et al., 2019;  
447 Wojcieszak and Wadley, 2019) were also recorded on the experimental shell before the  
448 heating experiment. These minerals likely come from soil particles present on the surface of  
449 the shell fragments. After heating (Table 2), carotenoids were still detected on shell fragments  
450 heated for less than 20 minutes at  $350^\circ\text{C}$ . They disappeared after this threshold. The  
451 transformation of aragonite into calcite was detected only in fragments heated for 5 minutes at  
452  $500^\circ\text{C}$ , in those heated for 20 minutes above  $450^\circ\text{C}$ , and those heated for 12 hours at a  
453 temperature of  $350^\circ\text{C}$ . Similar transition ranges in temperature and time were obtained on  
454 marine mollusc shells (Lange et al., 2008; Parker et al., 2010; d'Errico et al., 2015; Milano et  
455 al., 2016; Müller et al., 2017; Milano et al., 2018). Calcite is the most stable form of calcium  
456 carbonate at ambient conditions and can be distinguished from aragonite by the lower  
457 intensity bands in the wavenumber range below  $720 \text{ cm}^{-1}$ . Calcite characteristic Raman bands  
458 are located around 155, 282, 713 and  $1086 \text{ cm}^{-1}$  (Urmos et al., 1991). The aragonite to calcite  
459 transformation through heating depends on the temperature and the type of aragonite, it can  
460 take a few days at low temperature ( $\sim 100^\circ\text{C}$ ) or a few minutes at higher temperatures

461 (>470°C). For biogenic aragonite, the presence of intra-crystalline molecules intercalated in  
 462 the atomic structure influence the temperature of transition (Parker et al., 2010).



463  
 464 **Figure 6** Representative Raman spectra recorded on *Metachatina kraussi* experimental shell  
 465 fragments and Border Cave archaeological shell fragments. Tables 1 and 2 list the spectra  
 466 obtained for each specimen analysed. Most of the spectra presented were recorded on heated  
 467 experimental pieces, except for the spectrum of aragonite (centre), which was obtained from  
 468 an unheated experimental specimen, and the spectrum of gypsum (top), which was acquired  
 469 on an archaeological specimen.

470

471 For the archaeological samples (Table 1), only amorphous carbon, gypsum, manganese oxide,  
472 aragonite and calcite were detected. Amorphous carbon probably comes from the absorption  
473 of carbon from organic material surrounding the shell during the heating process (d'Errico et  
474 al., 2015) and from sediment particles. Gypsum could come from the sedimentary deposit and  
475 taphonomic processes that lead to the breakdown of organic matter, such as the introduction  
476 of fresh plant material like grass used for bedding, , wood used for fuel and guano from birds  
477 and bats (Schiegl and Conard, 2006). Manganese oxides may correspond to black stains  
478 present on the surface of some fragments (Figure 3). Dendritic structures, typical of  
479 manganese oxides (Potter and Rossman, 1979), were observed on an archaeological specimen  
480 using SEM-Energy Dispersive Spectroscopy (EDS) (Figure S3). Of the 27 archaeological  
481 specimens analysed, 12 contained aragonite. One specimen found in a layer dated to *c.* 60 ka  
482 still contains carotenoids. Calcite was recorded on nine specimens, often in combination with  
483 amorphous carbon; one was a mixture of both, and another was identified as bone. Because of  
484 high fluorescence, two samples produced spectra with no identifiable features and two others  
485 only produced spectra identifying calcium carbonate, with peaks around  $1084\text{ cm}^{-1}$ , but no  
486 bands distinguishing calcite from aragonite.

#### 487 3.4. *ATR-FTIR spectroscopy*

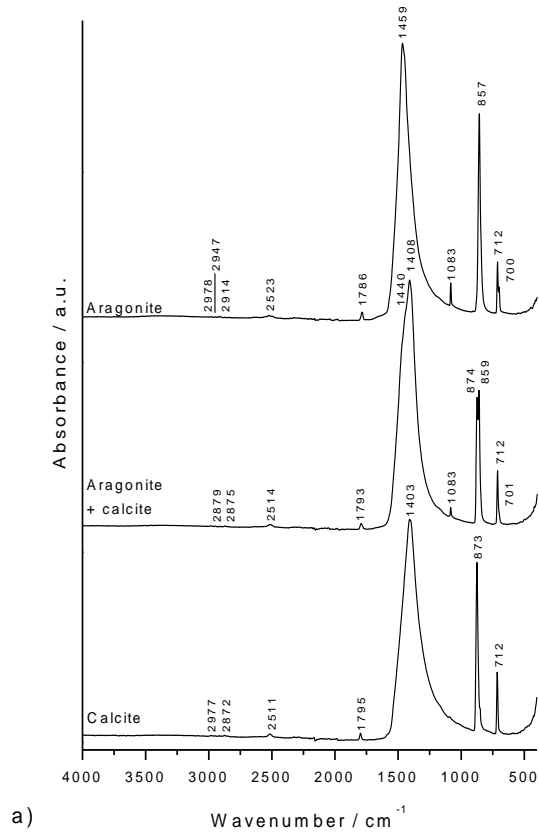
488 FTIR spectroscopy provides information on the molecular composition of the main  
489 compounds present in a sample; compounds present in low proportion will not be detected  
490 because they are covered by the more intense signal of the main compounds. For the  
491 experimental specimens (Figure 7a, Table 2), only two compounds were detected on unheated  
492 samples: aragonite with characteristic bands around 700, 712, 857, 1083, 1459, 1786, 2523,  
493 2947 and  $2978\text{ cm}^{-1}$  (Tomić et al., 2010) and organic matter with the CH stretching vibration

494 at 2914  $\text{cm}^{-1}$ . A mixture of aragonite and calcite was recorded on samples experimentally  
495 heated for 5 minutes at 500°C, on samples heated for 20 minutes at 400°C, and for 6 hours at  
496 350°C. The spectra with both aragonite and calcite signals exhibit a more pronounced  
497 asymmetry of the more intense vibrational band around 1400  $\text{cm}^{-1}$  in addition to a doublet at  
498 859 and 874  $\text{cm}^{-1}$ , clearly indicating the presence of both compounds. The characteristic band  
499 of organic matter was detected in coloured (beige or brown) samples heated at the lowest  
500 temperatures and/or for the shortest times. Carotenoids could therefore be responsible for this  
501 signal. One white sample also showed evidence of organic matter, but it was an uncleaned  
502 specimen, so the reading could be due to organic matter adhering to the surface of the shell.  
503 Only three specimens out of the 41 heated pieces identified only calcite, with bands around  
504 712, 873, 1403, 1795, 2511, 2872 and 2977  $\text{cm}^{-1}$  (Shillito et al., 2009; Tomić et al., 2010).  
505 These fragments were relatively thin. The above results suggest that the transformation of  
506 aragonite into calcite through heating depends on several parameters, such as the dimension  
507 and shape of the specimens, and the duration and temperature of heating, as previously  
508 mentioned. It also depends on the species analysed (Yoshioka and Kitano, 1985), hence the  
509 need for species-specific reference samples.

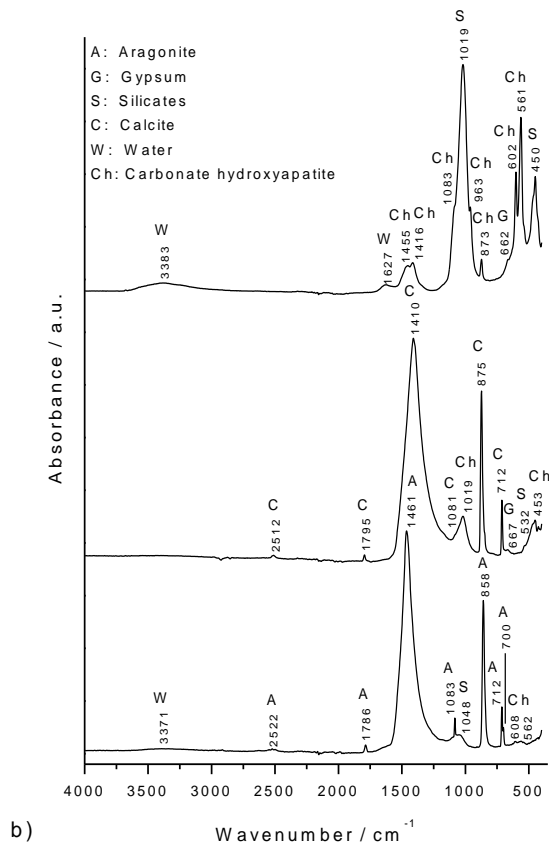
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513



514 **Figure 7.** Representative ATR-FTIR spectra recorded on a) modern *Metachatina kraussi*  
515 experimental shell fragments. The spectrum at the bottom corresponds to a white fragment  
516 heated at 550°C for 5 minutes; the spectrum in the middle to a fragment heated at 350°C for 6  
517 hours, and the top one to a fragment heated at 350°C for 1 hour, b) spectra obtained from  
518 Border Cave shell fragments of giant land snails.

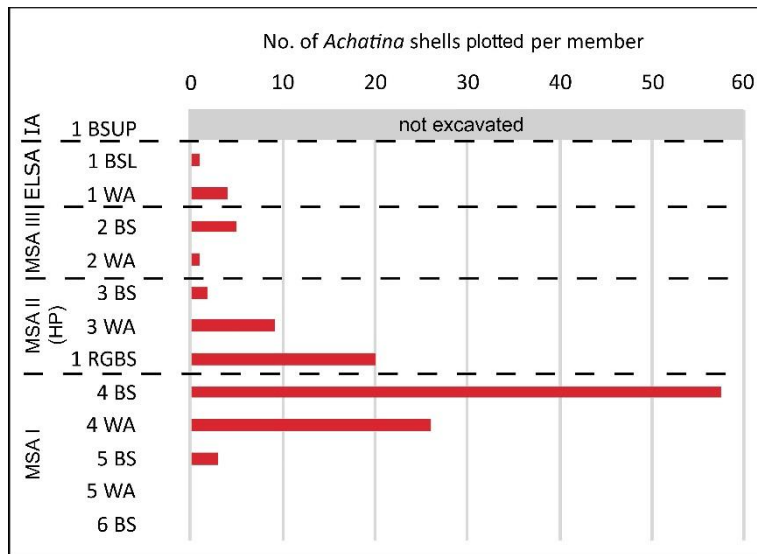
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520 The four archaeological specimens (see above) that did not provide identifiable Raman  
521 spectra, and two additional ones, were analysed by means of ATR-FTIR (Figure 7b). Two of  
522 them were identified as bone. Two others revealed the presence of aragonite and organic  
523 matter (CH vibrations at 2916 cm<sup>-1</sup> - data not shown) in addition to apatite and silicates, likely  
524 originating from sediment. The last two specimens contained calcite and silicates, and one of  
525 them gypsum.

### 526 3.5. *The stratigraphic distribution of Achatinidae fragments*

527 During the excavations conducted between 2015 and 2019 snail fragments were found in all  
528 archaeological members with the exception of the deepest ones (Members 5 WA and 6 BS).  
529 The fragments are particularly abundant in Member 4 BS and, to a lesser extent, in adjacent  
530 Members 4 WA, and 1 RGBS (Figure 8). The more recent archaeological deposits (Members  
531 2 WA, 2 BS, 1 WA), on the other hand, show a significant reduction in number, and here  
532 most of the pieces were found on grass mats. Shell fragments from the older members are  
533 abundant in layers with combustion features. In Member 5 BS two thirds of the fragments  
534 found in 2017 came from combustion features, while a quarter of the pieces found in Member  
535 4 BS were found in them. In this member the highest number of fragments (n = 252) found in  
536 one layer derive from a grass mat. This supports the hypothesis that the snails were cooked in  
537 combustion features and associated with human activity but does not eliminate the possibility

538 that the observed variations are also related to the availability of the resource in the  
 539 environment or to cultural changes.



540  
 541 Figure 8. Bar chart showing the number of *Achatina* shells plotted *in situ* per member from  
 542 2015–2019.

543  
 544 **4. Discussion and conclusion**

545 Our experimental results and those from previous studies indicate that shells of gastropods  
 546 composed of aragonitic layers undergo a change of mineral phase when heated at high  
 547 temperature or for a long time. The transformation of aragonite into calcite is generally  
 548 associated with change in colour, the appearance of microscopic cracks, the loss of water and  
 549 shell organic component, weight loss, and, at microscopic scale, the recrystallisation of  
 550 calcium carbonate from aragonite to calcite. Land snail heating for consumption does not  
 551 necessarily produce a mineral phase change and the above listed features. Experiments with  
 552 large edible *Helix* sp. indicate that roasting them on embers for 5-8 minutes was the most  
 553 plausible technique carried out at Pupićina cave, Croatia. This technique leaves barely visible  
 554 traces of burning (Rizner et al., 2009) and no mineral phase change when the shells were

555 analysed using XRD (Fernández-López de Pablo et al., 2014). However, the samples analysed  
556 presented some changes in the texture of aragonite, detectable from the relative intensities of  
557 the peaks in the diffractograms.

558 No complete or almost complete *Achatina* shells were recovered at Border Cave, including in  
559 the layers with few combustion features. This contradicts the possibility that live snails buried  
560 themselves in the sediments and were accidentally heated when humans made fireplaces at the  
561 site. Shells were not brought to the site to be used as raw material, for example for the  
562 production of beads or tools. No personal ornaments and artefacts made of these shells, nor  
563 production waste have been found at Border Cave. The hypothesis that *Achatina* were brought  
564 alive to the site to be cooked and consumed is consistent with the fact that fragments of this  
565 family are abundant in layers with combustion features. The presence of fragments made of  
566 aragonite, a mixture of aragonite and calcite, and calcite, is also consistent with the  
567 consumption contention (although diagenesis cannot be excluded): the large size of the  
568 *Achatina* is such that once put to cook on embers some parts of the shell may not reach the  
569 temperature necessary for the transformation of the aragonite into calcite. In addition, as  
570 mentioned above, the Pupičina Cave record shows that land snails can be satisfactorily  
571 cooked at temperatures lower than those involving a mineral phase change. It is likely that,  
572 considering its larger size, to fully cook an *Achatina* the mollusc must be exposed to heat for  
573 longer periods of time, which leads to a transformation into calcite of only the lower part of  
574 the shell in contact with embers. This would explain the mixture of burned and unburned shell  
575 fragments encountered in the same area during excavation, but add that this may be a result of  
576 diagenesis, which can be extremely localized. Combustion experiments have shown that the  
577 sediment below a fire can reach 300+°C through vertical heat transfer (Werts and Jahren,  
578 2007; Sievers and Wadley, 2008; Aldeias et al., 2016). This means that land snail shells in  
579 archaeological deposits, separated by thousands of years from fires made above them may be



580 thermally altered, and exhibit the same features as intentionally roasted snail shells. We  
581 acknowledge that no distinction can be made between intentional or fortuitous heating, as was  
582 the case for the blackened *Helix cincta* land snail shells dating from the Mesolithic Italian site  
583 of Edera Cave (Bonizzoni et al., 2009), and this may well have occurred with some pieces at  
584 Border Cave. However, baking of the sediment caused by overlying hearths made years later  
585 would have altered all of the fragments in a localised area, which is not the case; at Border  
586 Cave we find a mixture of transformed, partially transformed and unaltered shell fragments in  
587 close proximity. Heat transfer subsequent to deposition, which has probably had the effect of  
588 increasing the number of fragments made of calcite, does not explain how the snails arrived at  
589 the site in the first place, and why they are more abundant in layers with more combustion  
590 features. The most parsimonious explanation for the frequent presence of land snail shells in  
591 combustion features is that they were intentionally placed on coals, to cook them. Their  
592 occurrence in combustion features throughout the sequence, from about 170 ka ago, implies  
593 regular consumption of land snails at the site, with occupants of the shelter habitually eating  
594 them from 170–70 ka ago, and only occasionally thereafter, which makes Border Cave the  
595 earliest site at which the frequent consumption of land snails is recorded.

596 This finding has implications for our view of the evolution of diet within our lineage. Our  
597 results suggest that long before the broad spectrum revolution, human populations may have  
598 consumed terrestrial molluscs and for long periods. At Border Cave, as at other Middle and  
599 Later Stone Age sites in southern and eastern Africa, it would appear that they chose a species  
600 of particular nutritional value. However, the search for and consumption of this species, with  
601 such particular characteristics, did not necessarily imply a reorganization of the subsistence  
602 strategies of the human groups that exploited it, as was certainly the case with the advent of  
603 the broad spectrum revolution. The time dedicated to the collection of these molluscs did not  
604 impinge on that dedicated to hunting or other subsistence activities and did not require the

605 development of new technologies. Furthermore, snails could be easily collected by all mobile  
606 members of a band, regardless of their age or gender. Future research should apply the  
607 research strategy followed at Border Cave to other African sites that have yielded *Achatina*  
608 fragments, in order to gain a clearer picture of the regions and periods in which this species  
609 was exploited. It would be particularly important to establish whether *Achatina* fragments  
610 appear in other archaeological records of about 170 ka ago. There is growing evidence for  
611 consumption of marine molluscs at coastal sites from southern Africa (Marean et al., 2007;  
612 Jerardino and Marean, 2010) and Europe (Zilhão et al., 2020) dated to MIS 6 and MIS 5.  
613 Evidence for the consumption of land snails in those and subsequent periods has however  
614 been scant. This introduces the possibility that different populations, living in different  
615 environments, developed distinct cultural adaptations, including or not the consumption of  
616 molluscs, with inland cultural adaptations crossing the tipping point for consumption of  
617 molluscs later than some coastal populations. These scenarios need to be tested in the future  
618 by research focusing on the shell fragments found at inland sites. This may shed light on  
619 whether changes in the quantities of snail remains may be due to differential preservation,  
620 environmental changes probably reducing the availability of this resource during periods of  
621 increased aridity, or cultural change.

622 It may be no coincidence that between about 170 and 100 ka ago, we also found many charred  
623 whole rhizomes and fragments of the edible *Hypoxis angustifolia* in Border Cave (Wadley et  
624 al. 2020b). The implications of this discovery reach far beyond the interesting fact that people  
625 so far back in time cooked starchy foods. The cave is perched on a cliff where *Hypoxis* spp.  
626 do not grow, so collectors of the edible rhizomes would have dug them elsewhere and  
627 transported them to the home base for cooking and sharing. If sharing had not been intended,  
628 the food could have been eaten in the field where it was recovered. Ethnographic records of  
629 hunter-gatherer food collection, such as those made by Marshall (1976), clearly illustrate that

630 people eat a great many plants directly where they find them, and that hunters will also cook  
631 and eat some hunted meat in the field before carrying portions home. Thus, evidence from  
632 both the rhizomes and snails in Border Cave supports an interpretation of people in an  
633 economically active stage of life provisioning others (perhaps infirm band members and very  
634 young children) at a home base. The evidence therefore reaches beyond subsistence strategies  
635 and gives us a glimpse into the potentially complex social life of early *Homo sapiens*.

#### 636 **Author contributions**

637 M.W. and L.W. conceived the research. M.W. acquired and analysed the data and wrote the  
638 paper, with input from L.W., F.d'E. and L.B. L.W., F.d'E. and L.B. revised versions of the  
639 manuscript and made improvements to the text. Figures were produced by M.W. and L.B. All  
640 authors read and approved the final manuscript.

641

#### 642 **Declaration of competing interest**

643 The authors declare that they have no competing financial interests or personal relationships  
644 that could have influenced the work reported in this paper.

645

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665

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