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Argyro Nafplioti, Jan Driessen, Aurore Schmitt, Isabelle Crevecoeur. Mobile (after-)lifeways: People at pre- and protopalatial Sissi (Crete). *Journal of Archaeological Science: Reports*, 2021, 35, pp.102718. 10.1016/j.jasrep.2020.102718 . hal-03104928

**HAL Id: hal-03104928**

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1 **Title Page Information**

2

3 **Title:** Mobile (after-)lifeways: People at Pre- and Protopalatial Sissi (Crete)

4 **Author names and affiliation:**

5 Argyro Nafplioti<sup>a</sup> (corresponding author), Jan Driessen<sup>b</sup>, Aurore Schmitt<sup>c</sup>, Isabelle  
6 Crevecoeur<sup>d</sup>

7 <sup>a</sup>McDonald Institute for Archaeological Research, Downing Street,  
8 Cambridge CB2 3ER, e-mail: argyro.nafplioti@googlemail.com

9 <sup>b</sup>UCLouvain, Aegis/CEMA/INCAL, Belgium, e-mail: jan.driessen@uclouvain.be

10 <sup>c</sup>Aix Marseille Univ, CNRS, EFS, ADES, Marseille, France, e-mail:  
11 Aurore.SCHMITT@univ-amu.fr

12 <sup>d</sup>UMR 5199 PACEA, CNRS, Universite de Bordeaux, Pessac, France, e-mail:  
13 sabelle.crevecoeur@u-bordeaux.fr

14

15 **Abstract**

16 This paper discusses the first integrated strontium and oxygen isotope ratio results from  
17 human remains from Pre- and Protopalatial Crete, spanning the period circa 2500-1750 BCE,  
18 with a view to offering a more nuanced understanding of past populations, their diets,  
19 potential origins and aspects of their mobility: in particular, the extent to which mobility was  
20 part of these people's lives.

21 Twenty-six human individuals from the site of Sissi were sampled for strontium and  
22 oxygen isotope ratio in tooth enamel, while five of them were also analysed for corresponding  
23 strontium isotope signatures in bone samples. The human tooth enamel strontium isotope  
24 signatures follow a broad distribution that is in overall agreement with the diverse substrate  
25 geology reported for the site and its immediate surroundings, as well as with strontium  
26 isotope results from snail samples also collected from the broader Sissi region. In a fashion  
27 similar to the strontium data, the human oxygen isotope data point to access to different  
28 feeding territories in close proximity to the site and possibly also to variation in the  
29 composition of childhood diet, while some short-range immigration cannot be excluded  
30 either.

31 Isotope data variation and the inferred maximization of the exploitation of arable land  
32 to extend the agricultural resource base is largely in tune with contemporary socio-economic  
33 developments, settlement nucleation and population growth on Crete towards the late

34 Prepalatial period. Moreover, use of multiple production zones by the people at Sissi may also  
35 be seen as a buffer against climate instability and vulnerability of coastal sites.

36 Based on these data we conclude that mobility was part of the life of people at Sissi.  
37 They were either moving as part of their daily routine to exploit food resources, or in relation  
38 to marital network systems some of them had moved in from nearby sites, or both the above.

39

40 **Keywords:** isotopes, strontium, oxygen, provenance, mobility, diet, land use, Crete.

41

#### 42 **Highlights**

- 43 • First study of past human mobility on Crete using combined  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$   
44 evidence.
- 45 • The breastfeeding effect partly accounts for the high variation of the enamel  $\delta^{18}\text{O}$   
46 data.
- 47 • Results point to access to different feeding territories close to the site.
- 48 • Data variation is consistent with land use extensification linked to settlement  
49 nucleation, population growth and possibly climate instability in this period on the  
50 island.
- 51 • Overlapping  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  values across the island may obscure some short-  
52 range residential mobility linked to marital patterns.

53

54

55 **1. Introduction**

56 Diversity in mortuary behaviour on Early Bronze Age (3<sup>rd</sup> millennium BCE) Crete as  
 57 amply evidenced by funerary architecture and associated material culture and osteological  
 58 records has led to inferences about the possible diverse origins of the people buried  
 59 (Gkalanaki, 2020; Nafplioti, 2020, 2007; Legarra Herrero, 2009; Vavouranakis 2007). The  
 60 influence that the Cyclades, in particular, appear to have exercised during most of this time  
 61 over the rest of the Aegean, i.e. Euboea, Eastern Attica, the north-eastern Aegean islands and  
 62 further to the Aegean coast of Turkey, may also have extended to Crete (e.g. Betancourt,  
 63 2012; Day et al., 2012; Doonan and Day, 2007; Wilson et al., 2004; Papadatos, 1999; Carter,  
 64 1998; Day et al., 1998; Branigan, 1974, 1971). This has been the subject of opposing cultural  
 65 diffusion and population migration interpretative models. Based on these, the transfer of  
 66 material goods, ideas, practices and technologies outside the Cyclades resulted from contacts  
 67 and interaction with occasional if any gene flow from the Cyclades only, as opposed to the  
 68 idea that, any novelty was actually introduced by Cycladic people who moved and settled in  
 69 those sites, respectively (e.g. Sampson, A. and Hadji, 2019; Papadatos, 2007; Coleman, 1988;  
 70 Sampson, 1988: 126; Sapouna-Sakellarakis, 1987: 264; Doumas, 1977: 68, 1976: 77;  
 71 Mylonas, 1959: 162-3; Theocharis, 1959: 300; Childe, 1957: 51-52; Papavasileiou, 1910).  
 72 The case of Early Bronze Age Crete, however, probably lies somewhere in between, such that  
 73 the operating networks for trade and intermarriage of the time facilitated imports and the  
 74 adoption of Cycladic objects and practices by people on Crete, as well as some long-term  
 75 settlement of and mixing of newcomers within the local island population/s (Broodbank,  
 76 2000).

77 Until 40 years ago, archaeologists largely relied on material culture alone to explore past  
 78 population life-histories and used this evidence to investigate questions of provenance and  
 79 mobility (e.g. Scull, 1992; Branigan, 1984; Mee, 1982; Mellart, 1975; Warren, 1973;  
 80 Tringham, 1971; Caskey, 1960). Since the 1980's, however, initially in America and Northern  
 81 Europe but later also in the rest of the globe, biogeochemical analysis of archaeological  
 82 human skeletal remains has generated substantial new data on the lives of past people and  
 83 helped shed new light onto long-standing questions of mobility, cultural discontinuity and  
 84 change (e.g. Price, 2000; Ericson, 1985; van der Merwe, 1982; DeNiro and Epstein, 1981). In  
 85 this paper, we use human skeletal remains from Early and Middle Bronze Age or Pre- and  
 86 Protopalatial funerary contexts at Sissi on the north-east coast of Crete and employ for the  
 87 first time on human remains from the island integrated oxygen and strontium isotope ratio

88 analyses to offer a more nuanced understanding of past populations, their diets, potential  
89 origins and aspects of their mobility (Figure 1) (Chenery et al., 2010; Mitchell and Millard,  
90 2009; Knudson and Price, 2007). A sample of 26 individuals was analyzed.

91

92

## 93 **2. Background**

### 94 **2.1 Archaeological context**

95         Excavations by a team of the UCLouvain under the auspices of the Belgian School at  
96 Athens have been taking place at the seaside promontory site of Sissi since 2007 (Driessen et  
97 al., 2018, 2012, 2011, 2009). In 10 campaigns, substantial parts of a cemetery, settlement and  
98 ceremonial building have been uncovered (Figure 2). On present evidence, the site was  
99 occupied from Early Minoan IIA (c. 2600 BCE) onwards when a village was constructed on  
100 the southeast side of the promontory. It formed, together with Malia, part of a series of  
101 villages that existed along the coast of the Malia bay that extended from Stalidha to the west  
102 to Milatos to the east. From then onwards, the site of Sissi remained occupied till the  
103 advanced Late Minoan IIIB period (c. 1230 BCE), as did Malia. This longevity of occupation  
104 can undoubtedly be explained by its advantageous strategic location. Situated on a coastal hill  
105 with relatively steep sides and beaches on either side, the site is located opposite the Selinari  
106 Gorge, then and now the only route between Central and East Crete and an ideal  
107 communication artery, allowing interregional mobility. From EM IIA onwards, the north side  
108 of the hill housed a cemetery consisting a small stone buildings and compartments, known as  
109 House Tombs in Minoan archaeology (Schmitt and Sperandio, 2018; Crevecoeur et al., 2015;  
110 Schoep et al. 2012, 2011; Crevecoeur and Schmitt, 2009). Similar tombs have been excavated  
111 at Malia, Gournia, Mochlos, Petras and Palaikastro, for example, suggesting the presence of  
112 an especially East Cretan funerary tradition (Legarra Herrero, 2014). Other regions of the  
113 island followed other traditions, which could potentially imply a different cultural background  
114 and/or origins for the different communities. Although the House Tomb cemetery may have  
115 continued in use into the advanced Neopalatial period, at least where the higher terrace (Zone  
116 18) is concerned, many buildings were ruined earlier and some of these ruins were used to  
117 insert pithos burials especially during the Middle Bronze Age (e.g. Schoep et al., 2012: 32-  
118 35). The bioarchaeological and chronological analyses are still ongoing. However, the  
119 published preliminary reports (Driessen et al., 2018, 2012, 2011, 2009) provide sufficient data

120 to document and discuss the variability of strontium and oxygen isotope ratio values obtained  
121 from several individuals from the cemetery.

122         The 26 samples taken from skeletal remains for isotope analysis and presented in this  
123 paper come from burial structures that are located in various areas of the cemetery that  
124 spreads over three different terraces (Figure 3). On the lowest terrace in the east part (Zone 1),  
125 one collective burial<sup>1</sup> and one ossuary<sup>2</sup> (Crevecoeur et al., 2015), Burial Buildings 1.9 and  
126 1.10, were excavated, comprising respectively at least 11 and 20 individuals (Schoep et al.,  
127 2011: 64-66). From here come the five samples SAN 2 to 6. Further east, on a slightly higher  
128 first terrace, is a series of north-facing funerary buildings. While the plans of the spaces are  
129 relatively clear, there was not much earth deposition and erosion had taken its toll. Still, in  
130 some cases skeletal remains were sufficiently well preserved for sampling. From the higher,  
131 only partially excavated levels in spaces 1.30-31, a waste area resulting probably from tombs  
132 emptied, come samples SAN 12 and 13, while from the largest room, a collective burial 1.7,  
133 four samples were taken (SAN 14 to 17). On the second terrace, more to the west, one sample  
134 was taken in compartment 1.2 from Burial Building 1.1-1.3 (SAN 1). On the third and upper  
135 terrace, samples were taken both in the east part (Zone 1) and in the north zone of the  
136 cemetery (Zone 9), which is about 35 m to the west. In this north zone, there is a large Middle  
137 Minoan I-II Burial Building A (Schmitt and Sperandio, 2018) and from the first two  
138 excavated rooms 9.1-9.2, five samples (SAN 7 to 11) were taken. The west part of the east  
139 cemetery on the third terrace comprised a series of small stone compartments. The  
140 narrowness of the compartments and their bad preservation makes it difficult to discern a  
141 clear plan in the remains but from skeletal remains in one space (1.20) sample SAN 21 was  
142 taken. From skeletal remains in the corridor-like structure east (1.18) two more samples were  
143 taken (SAN 25-26). The eastern part of this terrace has at its core an EM IIB Burial Building  
144 with two compartments (1.11 and 1.12). Each room was sampled (SAN 18-24). This EM IIB  
145 tomb was partly overbuilt later and from this later room (space 1.17) we took two more  
146 samples (SAN 22-23). Two more samples were taken from a context (space 1.29) that is even  
147 at a higher level and probably even later (SAN 19-20). The plan in figure 3 shows that large  
148 parts of the cemetery were covered by this sampling, which can be considered as  
149 representative. Moreover, samples date from in between EM IIB to MM IIB (ca. 2500-1750  
150 BCE), and may hence also provide a chronological representativity. Table 1 provides  
151 information on burial practices (individual or commingled remains) and the type of samples.

---

<sup>1</sup> Successive burials through time in a single space

<sup>2</sup> Secondary deposit of incomplete individuals which is related to a ritualised management of space; it is a post-funerary practice.

152

153 **2.2. Strontium and oxygen isotope ratio analysis: principles**

154 Strontium and oxygen form two independent isotopic systems, which reflect local  
155 geology and climate respectively. As oxygen and strontium isotopes in teeth are fixed in  
156 enamel biogenic apatite at the time of tooth formation and enamel undergoes little  
157 remodelling thereafter, the isotope ratio values recorded reflect childhood provenance and  
158 provide complementary evidence for geographical origins and mobility (Hoppe et al., 2003;  
159 Hillson, 2002; Price et al., 2002, White et al., 1998).

160

161 **2.2.1 Strontium isotope ratio ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) analysis**

162 Strontium isotope ratios of human skeletal tissues are largely used as a proxy for local  
163 geology in order to determine the geographical origins of the individuals examined and  
164 distinguish between locals and non-locals. Since the principles of  $^{87}\text{Sr}/^{86}\text{Sr}$  analysis in  
165 research of this kind are well documented (Evans et al., 2009; Bentley, 2006; Price et al.  
166 2002), and have also been extensively discussed in earlier relevant work of one of the authors  
167 (e.g. Nafplioti, 2012a, 2011, 2008), the following is only a summary.

168 In nature, strontium occurs in the form of four stable isotopes,  $^{87}\text{Sr}$  (comprises c.  
169 7.04% of total strontium),  $^{88}\text{Sr}$  (c. 82.53%),  $^{86}\text{Sr}$  (c. 9.87%) and  $^{84}\text{Sr}$  (c. 0.56%). Strontium  
170 isotope  $^{87}\text{Sr}$  is radiogenic and is the product of the radioactive decay of the rubidium isotope  
171  $^{87}\text{Rb}$ , which has a half-life of approximately 47 billion years. All other three strontium  
172 isotopes are non-radiogenic (Faure, 1986). Therefore, in any geology the ratio of strontium  
173 isotope  $^{87}\text{Sr}$  to  $^{86}\text{Sr}$  depends on the relative abundance of rubidium and strontium at the time  
174 the rock crystallised and the age of the rocks (Rogers and Hawkesworth, 1989). Because  
175 rubidium is much more abundant in crustal materials than in the Earth's mantle, old  
176 metamorphic rocks of crustal origin have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  values (c. 0.715) than recent  
177 volcanic rocks (c. 0.704) (Wright 2005). Strontium isotope ratios in marine sedimentary rocks  
178 depend on the  $^{87}\text{Sr}/^{86}\text{Sr}$  value of seawater at the time they were formed and largely vary  
179 between 0.707 and 0.710 (Palmer and Elderfield, 1985; Elderfield, 1986)

180 In essence,  $^{87}\text{Sr}/^{86}\text{Sr}$  largely reflects local geology, and passes from the bedrock into  
181 the soil, the groundwater and the food chain. Thereby  $^{87}\text{Sr}/^{86}\text{Sr}$  reaches the human skeletal  
182 tissues, where it substitutes for calcium in hydroxyapatite (Faure 1986), largely from the food



183 and water consumed with no fractionation related to biological processes (Blum et al., 2000;  
184 Graustein, 1989). Although other factors such as proximity to marine environments and  
185  $^{87}\text{Sr}/^{86}\text{Sr}$  in sea spray (Veizer, 1989), atmospheric deposition (Miller et al., 1993) and in  
186 modern contexts fertilizers too, can also impact on local  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures, the latter largely  
187 reflect bedrock geology and mineral weathering (Bentley, 2006.). Thus  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures in  
188 human skeletal tissues match the geochemical profile of the catchment area of the individuals  
189 analysed.

190 Because tooth enamel is a cell-free tissue that for most of the permanent dentition  
191 largely forms by the 8<sup>th</sup> year of life and does not remodel thereafter (Hillson, 2002:148;  
192 Ubelaker, 1989),  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures from tooth enamel reflect early childhood diet and  
193 geographical origins. Conversely, bone and, to a lesser extent, also dentine, undergo  
194 continuous replacement of their mineral phase in the course of life. Thus cortical bone  
195  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures more closely reflect the dietary intake of the last 10 years of life, and  
196 human bone  $^{87}\text{Sr}/^{86}\text{Sr}$  values can be used to characterize local bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  at one's  
197 site of residence prior to death (Nafplioti, 2008; Tafuri et al., 2006; Ezzo and Price, 2002;  
198 Ezzo et al., 1997; Grupe et al., 1997; Price et al., 1994).

199 Acknowledging the possibility of recent immigrants amongst the individuals tested,  
200 samples from archaeological and/or modern animal skeletal tissues offer a more reliable  
201 measure of the local bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$ . They provide an average of the bioavailable  
202  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures of the feeding territories that these animals occupied in life and are  
203 thereby widely accepted as an accurate measure of the range of local  $^{87}\text{Sr}/^{86}\text{Sr}$  values in soils,  
204 plants, animals and waters in the areas investigated (e.g. Nafplioti, 2012a; Wright, 2005;  
205 Bentley et al. 2004; Price et al., 2002). Therefore, in principle, if an individual was born and  
206 raised in the local area, the  $^{87}\text{Sr}/^{86}\text{Sr}$  values measured from his/her tooth enamel should be  
207 similar to his/her bone  $^{87}\text{Sr}/^{86}\text{Sr}$  and the local bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures. They will also  
208 be in overall agreement to comparable data from local geological material(s). Otherwise, if  
209 tooth enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures are found to be significantly different from the local  
210  $^{87}\text{Sr}/^{86}\text{Sr}$ , we may infer that the respective people spent their childhood at (a) location(s)  
211 geologically and isotopically different from their residence prior to death.

212

213

214

## 215 2.2.2 Oxygen isotope ratio ( $^{18}\text{O}/^{16}\text{O}$ ) analysis

216 It is well-established that the oxygen isotope ratio ( $^{18}\text{O}/^{16}\text{O}$ ) of precipitation reflects  
217 the regional climatic conditions (i.e. temperature, humidity, distance from the sea and  
218 elevation) and decreases with distance from the sea, altitude, and falling temperature (Bowen  
219 and Revenaugh, 2003; Faure, 1986; Gat, 1980). Also,  $^{18}\text{O}/^{16}\text{O}$  values are negatively correlated  
220 with humidity levels (Darling *et al.*, 1996; Yurtsever and Gat, 1981).

221 Oxygen isotopes in the body of humans and other mammals are subject to several  
222 stages of metabolic fractionation from imbibed water, which is related to local precipitation  
223 (Longinelli, 1984; Luz *et al.*, 1984), to body fluids and from the latter to skeletal apatite. This  
224 fractionation is now adequately understood and predictable, so that approximate  $^{18}\text{O}/^{16}\text{O}$   
225 values for the imbibed meteoric water can be calculated and used to characterise the regional  
226 ecological context and probable geographic origins for the individuals analysed. Despite the  
227 difference between the oxygen isotope composition of the structural carbonate and phosphate  
228 components of bone or enamel apatite, oxygen of both the structural carbonate and phosphate  
229 of biogenic apatite has been demonstrated for modern mammals to be in equilibrium with  
230 body water (Daux *et al.*, 2008; Iacumin *et al.*, 1996; Kohn *et al.*, 1996; D'Angela and  
231 Longinelli, 1990; Levinson *et al.*, 1987; Longinelli, 1984). Also, there is a known quantitative  
232 relationship between the oxygen isotopic compositions of the two components of skeletal  
233 apatite (Bryant *et al.*, 1996; Iacumin *et al.*, 1996).

234 Tooth enamel  $^{18}\text{O}/^{16}\text{O}$  largely reflects the  $^{18}\text{O}/^{16}\text{O}$  in drinking water and also water  
235 in foods consumed by the individual during childhood, when teeth are formed (Hillson 2002),  
236 with some enrichment in  $^{18}\text{O}$  owing to metabolic fractionation. Moreover, tooth enamel  
237  $^{18}\text{O}/^{16}\text{O}$  values from teeth formed during the first few years of life, i.e. the incisors, canine and  
238 1<sup>st</sup> molar, when the individuals were most probably (still) breastfeeding, are enriched in  $^{18}\text{O}$   
239 ( $^{18}\text{O}/^{16}\text{O}$  values raised by ca. 1‰) compared to teeth that form following cessation of the  
240 breastfeeding, reflecting a trophic level effect (Wright and Schwarcz, 1998).

241 Determination of the local biologically available  $^{18}\text{O}/^{16}\text{O}$  is not as straightforward as  
242 for  $^{87}\text{Sr}/^{86}\text{Sr}$  above, owing to the difficulty in determining the various water sources used by  
243 the population tested and the possibility that exact values for prehistoric  $^{18}\text{O}/^{16}\text{O}$  and their  
244 patterning were different from  $^{18}\text{O}/^{16}\text{O}$  in modern precipitation. Additional complications  
245 come from inter-species variation in  $^{18}\text{O}/^{16}\text{O}$  values largely linked to physiology and dietary  
246 differences (Bentley and Knipper, 2005; White *et al.*, 2004; Kohn, 1996).

247 Moreover, owing to much overlap in human  $^{18}\text{O}/^{16}\text{O}$  values from different locations  
248 across continents, identifying probable geographical origins on the basis of oxygen isotope

249 analysis alone often is not possible (Lightfoot and O’Connell, 2016). Instead, the efficiency of  
250 oxygen isotopes for tracing the provenance of human skeletal remains is reinforced when  
251 combined with strontium and/or other isotope ratios such as isotopes of lead or sulphur, which  
252 serve as proxies for local geology rather than local environment (Redfern et al., 2016;  
253 Muldner et al., 2011; Turner et al., 2009).

254

255

## 256 **2.3 Geological context**

257 The island of Crete largely falls within the Gavrovo isotopic/tectonic zone, while its  
258 basement comprises nappes that represent rocks of several different environments, stacked up  
259 on top of each other during the Alpine compression (Higgins and Higgins, 1996: 197). The  
260 Gavrovo zone was a continental fragment for the early part of its history, where the Mesozoic  
261 shallow-water limestones were later almost completely covered up by late Eocene flysch  
262 sediments (Higgins and Higgins, 1996: 19).

263 The archaeological site of Sissi on the north-east coast of the island is set on a narrow  
264 strip of alluvium. Less than 1km to its south and further west extend Jurassic to Eocene thick  
265 bedded to massive limestones and dolomites of tidal to shallow water origin. For a small part  
266 to its south, these rocks are interrupted by an outcrop of the “Phyllite –Quartzite series” that  
267 contains rocks of different age, origin and grade of metamorphism. These include Permo-  
268 Triassic shales, phyllites, quartzphyllites and quartzites. Upper Miocene to Lower Pliocene  
269 limestones extend immediately to the east of the site, while no more than 5km further in the  
270 same direction occur older rocks, i.e. Jurassic to Eocene crystalline limestones with bands and  
271 nodules of chert (Creutzburg, 1977). The site of Sissi and its immediate periphery are thus  
272 characterized by high geological variability.

273

## 274 **3. Materials and Methods**

### 275 **3.1 Samples**

276 Strontium and oxygen isotope ratios were measured from tooth enamel samples from  
277 twenty-six individuals from different chronological contexts and locations within the Sissi  
278 cemetery chosen to span the entire site. Five of them were also analysed for corresponding  
279  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures in bone samples. The latter, including isotope ratio values from four snail

280 shell samples from the archaeological site of Sissi and the nearby village of Vrachasi, situated  
281 approximately 6 km to its south, which were used to characterize local bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  
282 are reported in Table 1.

283 All human teeth sampled had previously been studied macroscopically. The majority  
284 had been recovered as loose teeth (2 of the 26 teeth only were found attached to the associated  
285 maxillary/mandibular bone); hence it was not possible to confidently determine whether they  
286 belonged to male or female individuals or their precise age-at-death except for a few  
287 individuals only; all relevant information is included in Table 1.

288 For the purposes of  $^{18}\text{O}/^{16}\text{O}$  analysis, we aimed for the second permanent molar (M2),  
289 because the M2 enamel is known to form largely between the age of seven and eight (Scheuer  
290 and Black, 2000; Ubelaker, 1989) and therefore the measured  $^{18}\text{O}/^{16}\text{O}$  signatures are not  
291 expected to be affected by the consumption of mother's milk (Jay et al. 2008; Hoppe et al.,  
292 2003; Hillson, 2002; Montgomery, 2002; White et al., 2000; Wright and Schwarcz, 1998).  
293 This is known as the 'breastfeeding effect' where the oxygen isotope signal of enamel that  
294 mineralised during breastfeeding is raised by up to 1‰ over that of later forming teeth,  
295 reflecting the fact that nursing infants are feeding at a higher trophic level than their mothers.  
296 Where the M2, however, could not be sampled, it was substituted by the first molar (M1), an  
297 earlier forming tooth, and this will be taken into account in the discussion and interpretation  
298 of the results.

299

## 300 **3. 2 Sample preparation and analysis**

### 301 3. 2.1 Strontium isotope ratio analysis

302 The analytical protocol for  $^{87}\text{Sr}/^{86}\text{Sr}$  analysis, including procedures of sample  
303 extraction and sample preparation prior to analysis, have been described in earlier  
304 publications (Nafplioti 2008, 2009, 2011). Preparation and analysis of the samples were  
305 carried out at the National Oceanography Centre in Southampton, where the actual  $^{87}\text{Sr}/^{86}\text{Sr}$   
306 values were measured to the sixth decimal digit by a ThermoFisher TRITON Plus Thermal  
307 Ionization Mass Spectrometer (7 Collectors).

308

309

### 310 3.2.2. Oxygen isotope ratio analysis

311  $^{18}\text{O}/^{16}\text{O}$  was measured in the structural carbonate component of enamel apatite,  
312 because it is an easier, faster and less expensive method than measuring this in phosphate  
313 apatite, while it simultaneously recovers  $^{13}\text{C}/^{12}\text{C}$  values as well (Bryant et al. 1996; Bentley  
314 and Knipper 2005). Moreover, the isotope compositions of oxygen in the structural carbonate  
315 and phosphate components of bone or enamel apatite are related in a quantitative manner and  
316  $^{18}\text{O}/^{16}\text{O}$  carbonate values can easily be converted to the corresponding  $^{18}\text{O}/^{16}\text{O}$  phosphate  
317 values (see Bryant et al., 1996; Iacumin et al., 1996a).

318 Following abrasion of the external tooth crown enamel surface using a dremel tool,  
319 enamel powder of approximately 8-12  $\mu\text{g}$  was drilled out from the entire crown height  
320 avoiding to sample any adhering dentine. Enamel powders were then treated for bioapatite  
321 extraction following Balasse and colleagues (2002). After soaking samples in sodium  
322 hypochlorite 2–3% (24 h at 4°C) to remove organic matter, the samples were rinsed five times  
323 in distilled water and mixed with 0.1 M acetic acid (0.1ml/mg) for four hours at room  
324 temperature to remove exogenous carbonate. Following five rinses the samples were placed in  
325 the freezer at -20°C for 1 hour, and then at -80°C for an additional 30 minutes before being  
326 freeze dried for 90 minutes. The dried samples were then transferred into suitable tubes and  
327 placed into a VG SIRA mass spectrometer, where each sample was reacted with 100% ortho  
328 phosphoric acid at 70 °C. Liberated CO<sub>2</sub> was then trapped and transferred to the mass  
329 spectrometer for the isotopic analysis. Results are reported with reference to the international  
330 standard VPDB calibrated through the NBS19 standard (Hoefs, 1997; Coplen, 1995) in  
331 standard delta ( $\delta$ ) notation relative to the VPDB international standard and are expressed in  
332 units per mil (‰), i.e.  $\delta^{18}\text{O} = 1000 \times [(^{18}\text{O}/^{16}\text{O} \text{ sample}) / (^{18}\text{O}/^{16}\text{O} \text{ VPDB}) - 1]$ , (Table 1).

333 All oxygen isotope ratio measurements including sample preparation were carried out  
334 at the McDonald Institute for Archaeological Research, University of Cambridge. The long  
335 term analytical precision is better than  $\pm 0.08\text{‰}$  for  $^{13}\text{C}/^{12}\text{C}$  and better than  $\pm 0.10\text{‰}$  for  
336  $^{18}\text{O}/^{16}\text{O}$ .

337

## 338 4. Results

339 Strontium and oxygen isotope ratio results from the 26 individuals from Sissi analysed are  
340 displayed in Table 1 and Figs. 4 and 8.

341 The human tooth enamel strontium isotope ratios range between 0.70860 and 0.70971  
 342 (mean: 0.70939, 0.00048  $2\sigma$ ) (Table 1, Figures 4, 7 and 8). Variation is high, evidenced by  
 343 the large standard deviation and range (Table 2). It is higher than other Bronze Age human  
 344 skeletal collections in the South Aegean, viz. the Grave Circle A at Mycenae ( $\sigma=0.00002$ ), the  
 345 Ailias ( $\sigma=0.00010$ ), Gypsades ( $\sigma=0.00003$ ), and Sellopoulo ( $\sigma=0.00015$ ) collections from  
 346 Knossos, but lower compared with Manika on Euboea ( $\sigma=0.00065$ ), the Chora of Naxos  
 347 ( $\sigma=0.00044$ ) and Knossos South of the Palace ( $\sigma=0.00025$ ) (Nafplioti 2007, 2008, 2009a,  
 348 2009b, 2012b).

349 Strontium isotope signatures from snails collected from the excavation site (1) and  
 350 the neighbouring village of Vrahasi (3) range between 0.70783 and 0.70974. Variation for the  
 351 snail isotope values (mean: 0.70863, 0.00176  $2\sigma$ ) is higher compared to the human tooth  
 352 enamel signatures. By contrast, the human bone strontium isotope signatures from the site are  
 353 more homogeneous and range from 0.70928 to 0.70944 (mean: 0.709301, 0.00016  $2\sigma$ ).

354 Oxygen isotope ratios from tooth enamel carbonate from the same individuals yielded  
 355  $\delta^{18}\text{O}_c$  values which are reported relative to the VPDB international standard. In order to  
 356 facilitate comparison of the human  $\delta^{18}\text{O}_c$  values to local precipitation data from the region and  
 357 further explore provenance for the respective individuals we converted the carbonate oxygen  
 358 VPDB data to carbonate oxygen VSMOW values using the equation below (1)

359  $\delta^{18}\text{O VSMOW} = (1.0309 \times \delta^{18}\text{OVPDB}) + 30.9$  (1) (Friedman and O'Neil 1977; Henton, et  
 360 al. 2010, 439)

361 and calculated the corresponding  $\delta^{18}\text{O}$  values for drinking water ( $\delta^{18}\text{O}_{\text{dw}}$ ). Converting the  
 362 human phosphate  $\delta^{18}\text{O}$  to  $\delta^{18}\text{O}$  water signatures allows comparability to data from modern  
 363 precipitation and outweighs any concerns with the choice of appropriate published equation  
 364 or with error propagation (Pryor et al., 2014; Chenery et al., 2012; Pollard et al., 2011;  
 365 Chenery et al., 2010; Daux et al., 2008; Levinson et al., 1987; Luz and Kolodny, 1985;  
 366 Longinelli, 1984). To this end we used the equation formulated by Daux *et al.* (2008)  
 367 modified following Iacumin and colleagues (1996) to reflect the correlation between  $\delta^{18}\text{O}$   
 368 values measured in the structural carbonate and phosphate components of apatite,  
 369 respectively, as follows (2, 3):

370  $\text{If } \delta^{18}\text{O}_{\text{mw}} = 1.54 (\pm 0.09) \times \delta^{18}\text{O}_p - 33.72 (\pm 1.51)$  (2) Daux *et al.* (2008)

371 and

372  $\delta^{18}\text{O}_p = 0.98 \times \delta^{18}\text{O}_c - 8.5$  (3) (Iacumin *et al.* 1996a)

373 Then

374  $\delta^{18}\text{O}_{\text{mw}} = 1.51 \times \delta^{18}\text{O}_c - 46.81$

375 The results of the above calculations are given in Table 1.

376 As was observed from the  $^{87}\text{Sr}/^{86}\text{Sr}$  human tooth enamel data, the  $\delta^{18}\text{O}_p$  values from the same  
 377 individuals follow a rather broad distribution, from 17.3‰ to 19.9‰ (mean  $18.7 \pm 1.2\%$ ,  $2\sigma$ )  
 378 with corresponding drinking water values between -7.3 ‰ and -3.4‰ (mean  $-5.3 \pm 1.7\%$ ,  $2\sigma$ )  
 379 (Table 1, Figure 4).

380

381

## 382 5. Discussion

### 383 5.1 Variation in strontium isotope ratios

384 Provided that the substrate local geology within the catchment area is rather  
 385 homogeneous, human tooth enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures at any given site are expected to be  
 386 normally distributed for people who were born and raised locally, subsisted on more or less  
 387 the same locally-grown or locally-procured foods, i.e. there was no differential access to food  
 388 resources of any kind, and were not appreciably mobile (Wright 2005). Descriptive statistics  
 389 applied to the Sissi human tooth enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  data suggest a significant deviation from a  
 390 normal distribution (Shapiro-Wilk Test:  $p=0.019$ ) (Table 2). Distribution of the  $^{87}\text{Sr}/^{86}\text{Sr}$   
 391 signatures is leptokurtic, i.e. it has a positive kurtosis, and it is also skewed towards values  
 392 higher than the mean, resulting in a median that is higher than the mean. The above are  
 393 illustrated in Figure 5, where an estimated normal distribution curve is also plotted for  
 394 comparative purposes. The enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.70860 (SAN7) lays more than  $2\sigma$  away  
 395 from the mean  $^{87}\text{Sr}/^{86}\text{Sr}$  of the Sissi assemblage, and thus stands out at the left tail of the  
 396 distribution curve as a possible outlier, i.e. a non-local at Sissi. When this outlier is eliminated  
 397 from the dataset, the now trimmed data appear to follow a normal distribution (Shapiro-Wilk  
 398 Test:  $p=0.739$ ); intra-group variation is lower ( $\sigma=0.00018$ ) compared to the complete data set;  
 399 mean (0.70942) and median (0.70945) are closer (Table 2, Figure 6).

400 Albeit not statistically justified, additional values at the tails of the distribution may  
 401 also indicate non-locals at Sissi, or people who moved at Sissi when they were very young,  
 402 i.e. while tooth enamel for the permanent dentition was still forming (Figure 6). Nonetheless,

403 it is not clear where exactly in the distribution one should safely draw the boundaries for the  
404 local Sissi population. Data on the local biologically available  $^{87}\text{Sr}/^{86}\text{Sr}$  on the one hand, and  
405 information on the local geology and the site's distance from the sea on the other, may  
406 therefore prove useful in this respect.

407 Figure 7 plots the human tooth enamel and bone  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures together with  
408 data on the local biologically available  $^{87}\text{Sr}/^{86}\text{Sr}$  measured from snail shells from the site and  
409 the broader region. The human cortical bone values reflect adult diet during the last 10-15  
410 years or so in one's life and follow a narrower distribution than the tooth enamel ratios. This  
411 is not surprising as tooth enamel ratios reflect a much narrower period, i.e. a maximum of 2 to  
412 3 years in early childhood. Additionally, bone is more susceptible to post-depositional  
413 contamination, which would potentially narrow isotope ratio variation down to the isotope  
414 ratio signatures of the burial environment. Bone isotope signatures are also less variable than  
415 the ratios measured from the snail shells.

416 Snail shell  $^{87}\text{Sr}/^{86}\text{Sr}$  values are in good agreement with the highly variegated substrate  
417 geology for the broader Sissi region where limestones of different age and old metamorphic  
418 rocks occur in a radius of just 5km, as described in Section (2.3) above. Intra-group variation  
419 ( $\sigma=0.00088$ ) for the four snail samples is higher compared to the human enamel values, while  
420 the actual values range between 0.70783 and 0.70974. The latter was measured from a  
421 specimen collected from the excavation site, while the remainder three  $^{87}\text{Sr}/^{86}\text{Sr}$  shell values  
422 average at  $0.70830 \pm 0.00062$  and were measured from the three Vrachasi village snails. All  
423 26 human enamel ratios in fact fall within the range of the snail ratios and can therefore be  
424 identified as locals within the broader region of Sissi (Figures 4 and 8).

425 If we look carefully at the Sissi human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  data, these generally fit  
426 provenance in coastal areas where marine strontium from seaspray, rainwater and shell sands  
427 have a significant impact on the local biosphere Sr values, i.e. around 0.7090-0.7092  
428 (Montgomery et al., 2007; Bentley, 2006: 153; Montgomery et al., 2003; Veizer, 1989).  
429 Nonetheless, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value from individual SAN7, who was statistically identified as an  
430 outlier, falls below the modern seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  constant of 0.7092 (Veizer 1989). Albeit not  
431 compatible with an origin from a coastal site, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value from SAN7 does not exclude  
432 an origin within the island. Strontium isotope ratios similar to SAN7 from Burial Building  
433 9.1, although rare amongst the local bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures from Crete, are not  
434 altogether absent. In fact, the two lowest  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures from the Vrachasi snails  
435 measured as 0.70783 and 0.70807 suggest that it would not be illegitimate to infer that SAN7  
436 was local at the broader Sissi region. Similarly low isotope values from the rest of the island,



437 including a published value of 0.70853 measured from a sheep/goat from Bronze Age  
438 Knossos (Nafplioti 2011: 1564, 1567), as well as more data currently under preparation for  
439 publication (Nafplioti, in preparation) further corroborate a provenance within the island for  
440 the individuals in question.

441         The remainder of the Sissi human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  values range between 0.70903 and  
442 0.70971 and average at  $0.70942 \pm 0.00018$ . More than half of these values fall within the  
443 range of the mean human bone  $^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$  (0.70915 to 0.70946) and can thus be identified  
444 as locals at Sissi. Moreover, based on the  $^{87}\text{Sr}/^{86}\text{Sr}$  signature from the snail from the  
445 archaeological site (0.70974), the more radiogenic human enamel values, i.e. those between  
446 0.7096 and 0.7097, can also be identified as locals at the site.

447         In the context of high variation in the underlying geology of the region, the more  
448 radiogenic enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures probably reflect older geological formations and  
449 different catchment areas for the respective individuals compared to burials with lower  
450  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures that are close to the seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  constant. The human enamel  
451  $^{87}\text{Sr}/^{86}\text{Sr}$  results therefore point to extensification of land use in this period and access to  
452 different feeding territories in close proximity to the site (e.g. Haggis, 1999: 64; Manning,  
453 1994: 234), for instance within a radius of a couple of kilometers. The use of multiple  
454 production zones by the Sissi people can also be seen as a buffer against climate instability  
455 and vulnerability of coastal sites (Moody, 2012: 259-64). To some extent variation in human  
456 enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  values, may also reflect variation in the composition of people's childhood  
457 diet in terms of proportions of foodstuffs of higher and lower strontium concentration and of  
458 different associated  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures: for instance meat and milk that contain less strontium  
459 compared to plant foods will have a rather small impact on the average human skeletal  
460 strontium isotope signatures compared to that of the strontium-rich plants consumed by the  
461 respective people (Montgomery and Evans, 2009: 125). Alternatively, some of the Sissi  
462 individuals may have been born and raised in nearby sites, so that the observed high human  
463 enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  variation may also reflect small-scale, short-range intra-island residential  
464 mobility. This probability, however, cannot be adequately assessed using strontium data alone  
465 due to overlapping bioavailable strontium isotope signatures across parts of the island linked  
466 to similarities in the underlying geology (Nafplioti, 2011, 2015). Nor can we test for any sex-  
467 pattern in data variation and whether marital patterns may (partly) account for any intra-island  
468 residential mobility (as demonstrated in Bentley et al., 2005), owing to the small number of  
469 Sissi individuals, who could be confidently sexed.

470

## 471 5.2 Variation in oxygen isotope ratio values

472 The human enamel  $\delta^{18}\text{O}_p$  signatures on Figure 4 follow a rather broad data distribution  
473 (17.3‰ to 20.0 ‰ (mean  $18.7 \pm 1.2\%$ ,  $2\sigma$ ). To a great extent this probably also reflects the  
474 breastfeeding effect and the enrichment of  $\delta^{18}\text{O}_p$  values from the M1s analysed. If we correct  
475 for this effect by subtracting 1‰ from the M1  $\delta^{18}\text{O}_p$  values, the  $\delta^{18}\text{O}_p$  range narrows down to  
476 between 16.9‰ and 19.0 ‰ (mean  $17.8 \pm 1\%$ ,  $2\sigma$ ) with corresponding drinking water values  
477 between -7.9‰ and -4.9‰ (mean  $-6.4 \pm 1.7\%$ ,  $2\sigma$ ) (Table 1, Figure 8).

478 Due to the lack of empirical data on the range of oxygen isotope ratio variation for  
479 the local Sissi population, as we have for other sites where the local  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures could  
480 be used to determine corresponding local  $\delta^{18}\text{O}_p$  values (e.g. Hughes et al 2014; Eckardt et al.,  
481 2009), we were not able to determine local  $\delta^{18}\text{O}_p$  ranges for humans in this context. Instead  
482 we used published  $\delta^{18}\text{O}$  data on modern precipitation (Lykoudis and Argyriou, 2007) to  
483 extrapolate what might be acceptable drinking water  $\delta^{18}\text{O}$  values for the Bronze Age  
484 inhabitants of Sissi. These data suggest that modern  $\delta^{18}\text{O}_{\text{mw}}$  values across Crete range  
485 between -5 and -7‰ with the more positive values occurring on the coastal areas and the  
486 more negative towards the interior of the island. These data thus are in good overall  
487 agreement with the  $\delta^{18}\text{O}_{\text{dw}}$  values measured from the Sissi individuals and with provenance  
488 within the island that had also been suggested based on the corresponding strontium isotope  
489 data.

490 Due to overlapping strontium and oxygen isotope signatures between the central  
491 Cyclades and the site of Sissi, the results cannot be used to test a Cycladic presence at the site.  
492 The resolution of modern precipitation  $\delta^{18}\text{O}$  data from Crete and the south Aegean (Lykoudis  
493 and Argyriou, 2007) is unfortunately not high enough to clearly separate between sites on  
494 Crete and the Cyclades. On Crete, however, the data rather show general differences  
495 depending on proximity to the sea and/or altitude for sites/parts of the island. In this respect,  
496 the human  $\delta^{18}\text{O}_{\text{dw}}$  signatures appear to reflect the variation of modern precipitation  $\delta^{18}\text{O}$   
497 signatures observed among different parts of the island; thus suggesting that the oxygen data  
498 reflect climatic variation and probably represent more than one site.

499 Two additional points that will be worthwhile to look into are the potential chronological  
500 and/or spatial patterning of human isotopic data. Because studies on the chronology of the  
501 bioarchaeological data of the site are in progress we are not yet able to conclusively discuss  
502 these, once these studies are completed and the relevant data are finalized we will examine

503 them against the isotopic data from the site with a view to furthering our understanding of the  
504 observed data variation.

505

## 506 **6. Conclusions**

507 The human strontium and oxygen isotope signatures are in line with a local origin  
508 within the broader region of Sissi. The strontium isotope values, in particular, point to a  
509 diverse substrate geology in agreement with that reported for Sissi and its immediate  
510 surroundings within a 5km radius (Creutzburg, 1977), while the oxygen data match the  
511 variation of modern precipitation  $\delta^{18}\text{O}$  values from different parts of the island and point to  
512 variability in climate linked to distance to the sea and/or altitude. The human strontium and  
513 oxygen results thus point to the use of different feeding territories in proximity to the site and  
514 possibly also variation in childhood diet. It seems therefore plausible that at Pre- and  
515 Protopalatial Sissi short-range mobility that needed not exceed a radius of 5km was part of  
516 people's lives. Either they were moving as part of their daily routine to cultivate the land,  
517 herd their flocks and/or hunt or fish, or some of them had relocated from sites nearby, or even  
518 both.

519 Maximization of the exploitation of arable land to extend the agricultural resource  
520 base largely coincides with settlement nucleation and population growth towards the late  
521 Prepalatial period, while use of multiple production zones by the people at Sissi may also be  
522 seen as a buffer against climate instability and vulnerability of coastal sites.

523 Due to overlapping strontium and oxygen isotope signatures it is impossible to choose  
524 between potential sites of origin within the island of Crete or the central Cyclades. Even if  
525 nonlocals are indeed present amongst the Sissi individuals tested, based on information of the  
526 substrate geology of the island and modern precipitation  $\delta^{18}\text{O}$  data, they did not need to have  
527 originated from outside Crete or sites on the island at a great distance from Sissi. They could  
528 have moved in from nearby villages across the Malia bay, such as the roughly contemporary  
529 site of Malia to the west, or the Neapolis area to the south-east of Sissi, respectively.  
530 Although we cannot discard this scenario, based on the bioavailable strontium and modern  
531 precipitation oxygen data from the broader Sissi region we favor the theory for a local origin  
532 within this region and mobile lifeways at least for the majority of the people studied.

533

534 **Acknowledgments**

535 We are grateful to the Ephorate of Antiquities of Lasithi for facilitating our research at Sissi  
 536 in general and on diet and mobility in particular and also for their permission to sample the  
 537 archaeological skeletal collection from the site for the purposes of this work. Research at Sissi  
 538 is funded by the UCLouvain, INSTAP, the Belgian School at Athens, the Loeb Classical  
 539 Library, the Rust Family Foundation, the FNRS, the CNRS and private sponsors. Travel  
 540 expenses and the analytical costs for the oxygen isotope ratio analysis were covered through  
 541 research funding from a Marie Skłodowska-Curie Individual Fellowship and a grant from the  
 542 D.M. McDonald Grants and Awards Fund that were both awarded to A. Nafplioti for her  
 543 project entitled EPOCH GeoChem (project number 654736), while the Katholieke  
 544 Universiteit Leuven via I. Schoep sponsored the strontium analyses. Without the above  
 545 financial support this research would not have been possible.

546

547

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**List of tables**

Table 1.  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  ratios from and basic archaeological and anthropological information on the individuals sampled from Sissi.

Table 2. Descriptive statistics for  $^{87}\text{Sr}/^{86}\text{Sr}$  values from Sissi human enamel, for the complete and trimmed data sets.

## List of Figures

Figure 1. Map of the Aegean; marked on it is the site of Sissi.

Figure 2. Site plan of Bronze Age Sissi on Crete showing all zones excavated.

Figure 3. Plan of the Pre- and Protopalatial cemetery at Sissi showing the locations where the samples analysed were recovered from (edited by J. Driessen).

Figure 4. Strontium and oxygen (phosphate and calculated drinking water values) isotope ratios for individuals from Sissi.

The circle denotes samples from M1s which are probably affected by the breastfeeding effect. The star and triangle mark M2s and M3s, respectively, which form after individuals were weaned. Shown on the graph are the estimated range of bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures measured from snails found within a 6 km radius around Sissi, and the range for the oxygen isotope composition of modern precipitation on Crete (after Lykoudis and Argyriou 2007).

Figure 5. Histogram of the complete Sissi human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  data set, with normal distribution curve for comparison.

Figure 6. Histogram of the trimmed Sissi human enamel  $^{87}\text{Sr}/^{86}\text{Sr}$  data set, with normal distribution curve for comparison.

Figure 7. Strontium isotope ratio ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) values from human enamel samples from Sissi and snail shell values from the broader region.

Key: BARS: black=human dental enamel, white=human bone, grey= snail shell.

Figure 8. Strontium and corrected oxygen (phosphate and calculated drinking water values) isotope ratios for individuals from Sissi.

The circle denotes oxygen values from M1s corrected for a potential breastfeeding effect, while the star and triangle mark M2s and M3s, respectively, which form after individuals were weaned.





Figure 2

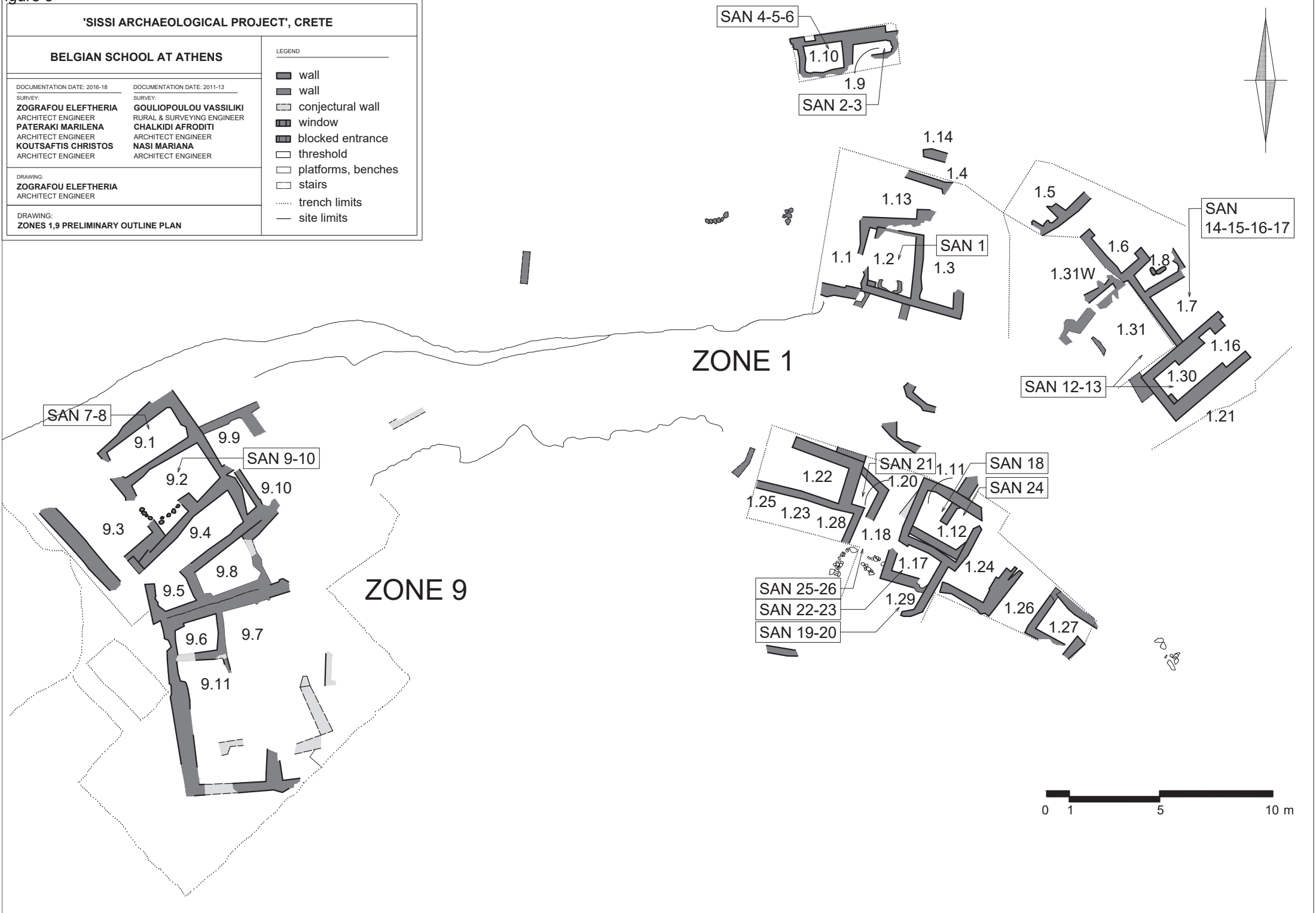
[Click here to access/download;Figure;Figure 2.jpg](#)

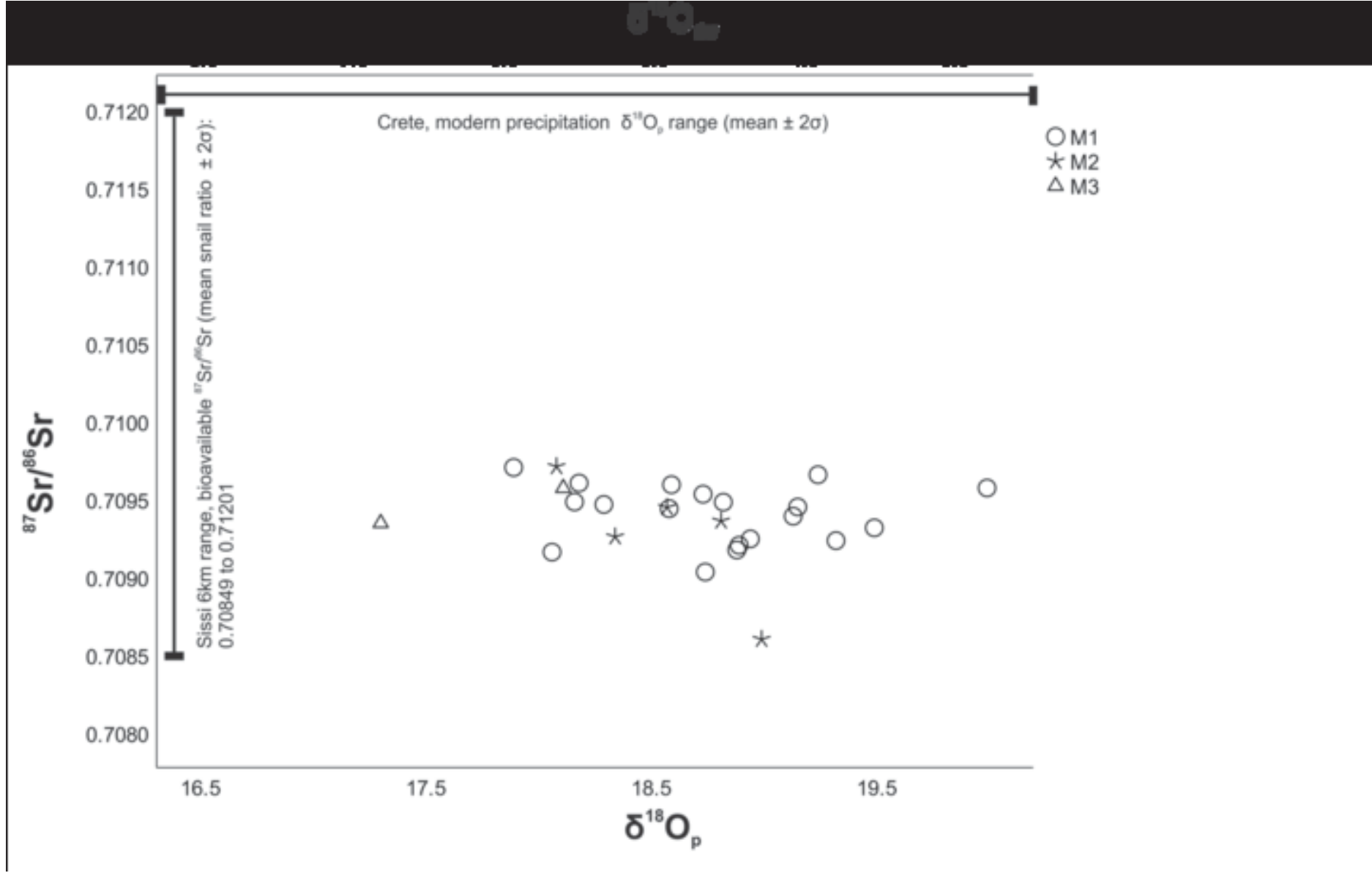


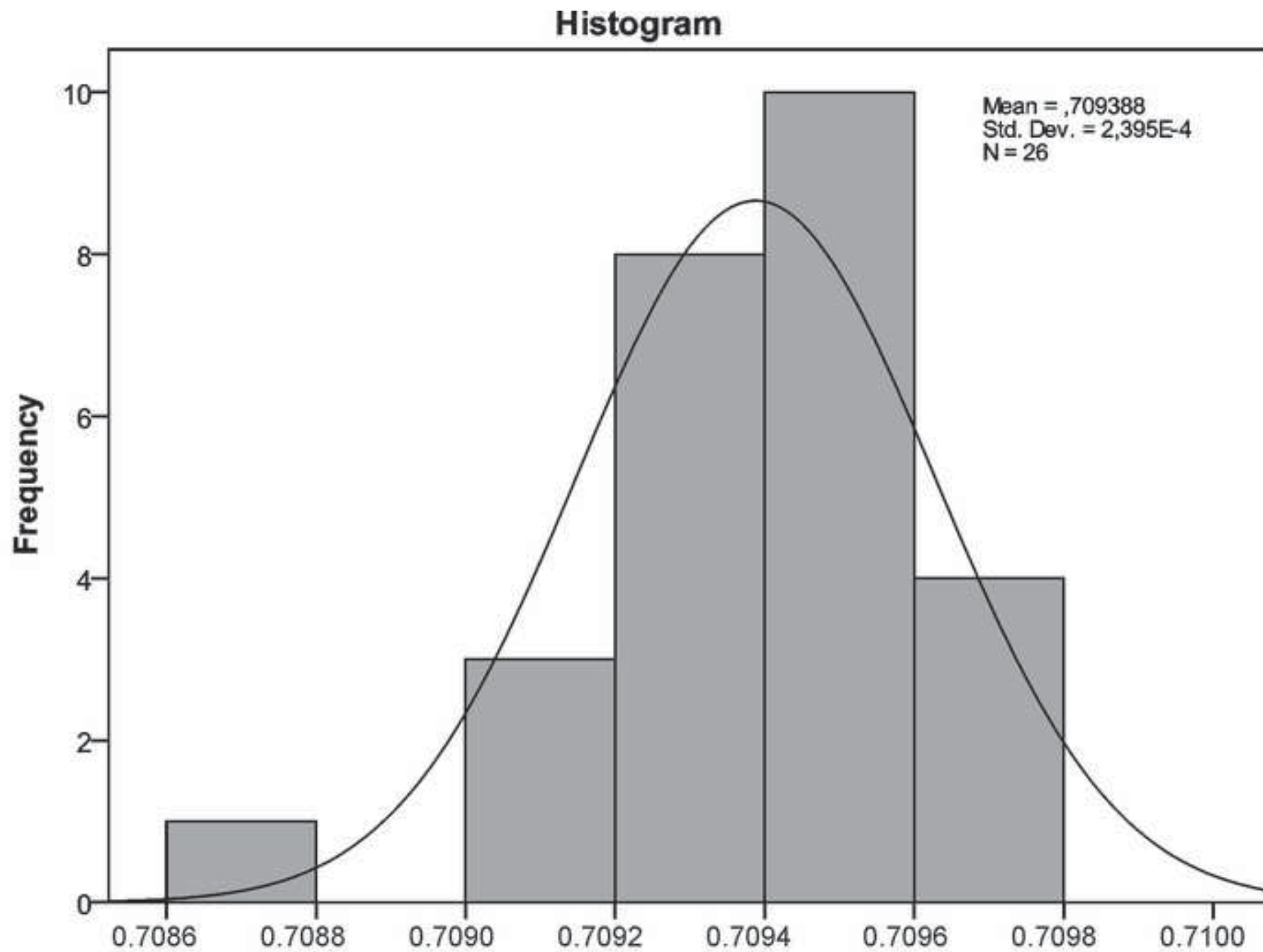
Figure 3

'SISSI ARCHAEOLOGICAL PROJECT', CRETE	
BELGIAN SCHOOL AT ATHENS	
DOCUMENTATION DATE: 2016-18	DOCUMENTATION DATE: 2011-13
SURVEY: <b>ZOGRAFOU ELEFThERIA</b> ARCHITECT ENGINEER <b>PATERAKI MARILENA</b> ARCHITECT ENGINEER <b>KOUTSAFTIS CHRISTOS</b> ARCHITECT ENGINEER	SURVEY: <b>GOULIOPOULOU VASSILIKI</b> RURAL & SURVEYING ENGINEER <b>CHALKIDI AFRODITI</b> ARCHITECT ENGINEER <b>NASI MARIANA</b> ARCHITECT ENGINEER
DRAWING: <b>ZOGRAFOU ELEFThERIA</b> ARCHITECT ENGINEER	
DRAWING: <b>ZONES 1,9 PRELIMINARY OUTLINE PLAN</b>	

- LEGEND
- wall
  - wall
  - conjectural wall
  - window
  - blocked entrance
  - threshold
  - platforms, benches
  - stairs
  - trench limits
  - site limits







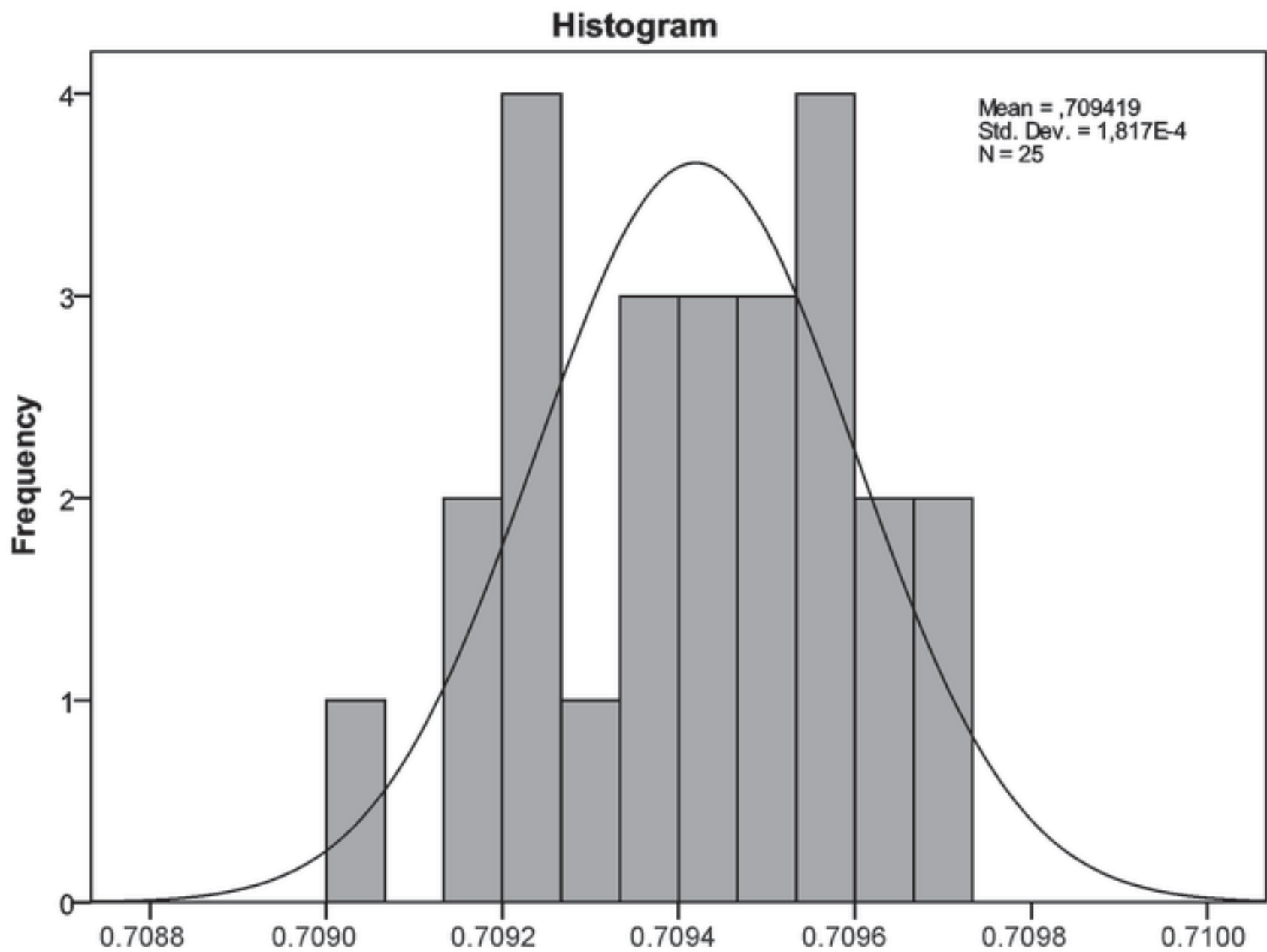
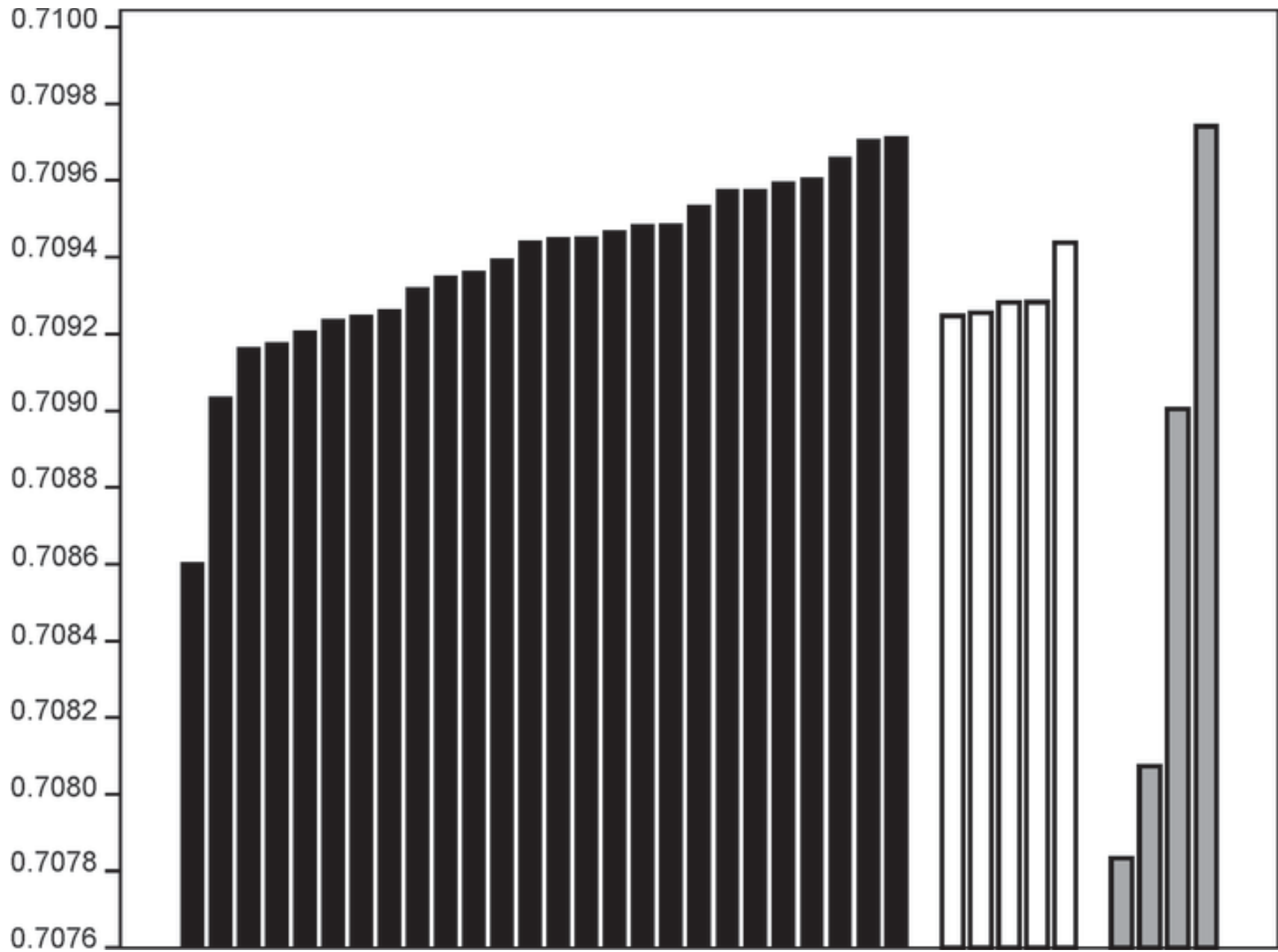
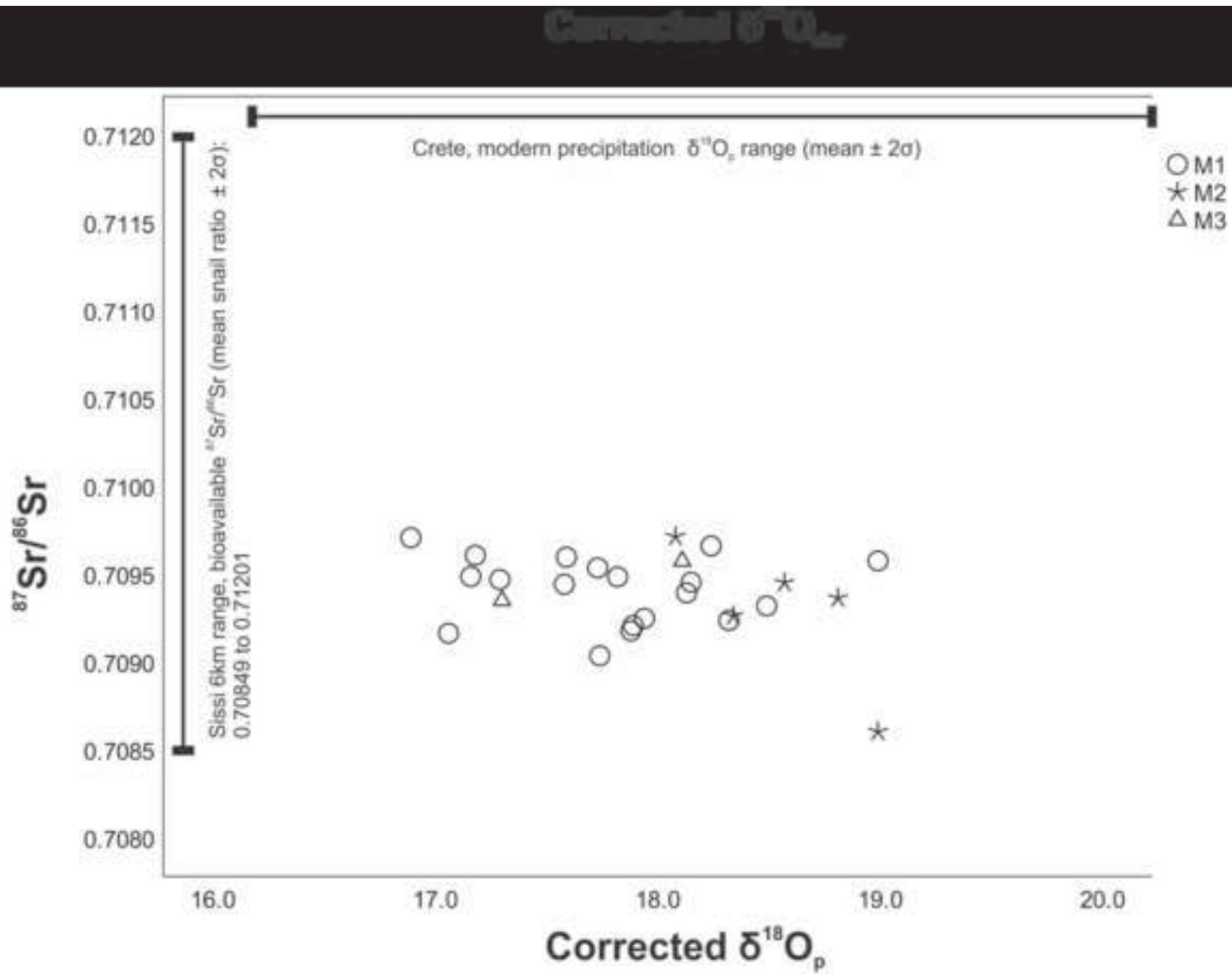


Figure 7









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**Table**

Table 1.docx



