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1 **Title Page Information**

2

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

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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 (3rd 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 burial¹ and one ossuary² (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.

¹ Successive burials through time in a single space

² 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}Sr (comprises c.
169 7.04% of total strontium), ^{88}Sr (c. 82.53%), ^{86}Sr (c. 9.87%) and ^{84}Sr (c. 0.56%). Strontium
170 isotope ^{87}Sr is radiogenic and is the product of the radioactive decay of the rubidium isotope
171 ^{87}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}Sr to ^{86}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 8th 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}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 1st molar, when the individuals were most probably (still) breastfeeding, are enriched in ^{18}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 μg 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 CO₂ 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 (δ) 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 2σ) (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 2σ) 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 2σ).

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 $18.7 \pm 1.2\%$, 2σ)
 378 with corresponding drinking water values between -7.3 ‰ and -3.4‰ (mean $-5.3 \pm 1.7\%$, 2σ)
 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 2σ 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 ± 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 ± 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 $18.7 \pm 1.2\%$, 2σ). 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 $17.8 \pm 1\%$, 2σ) with corresponding drinking water values
477 between -7.9‰ and -4.9‰ (mean $-6.4 \pm 1.7\%$, 2σ) (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

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546

547

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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) .

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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](#)

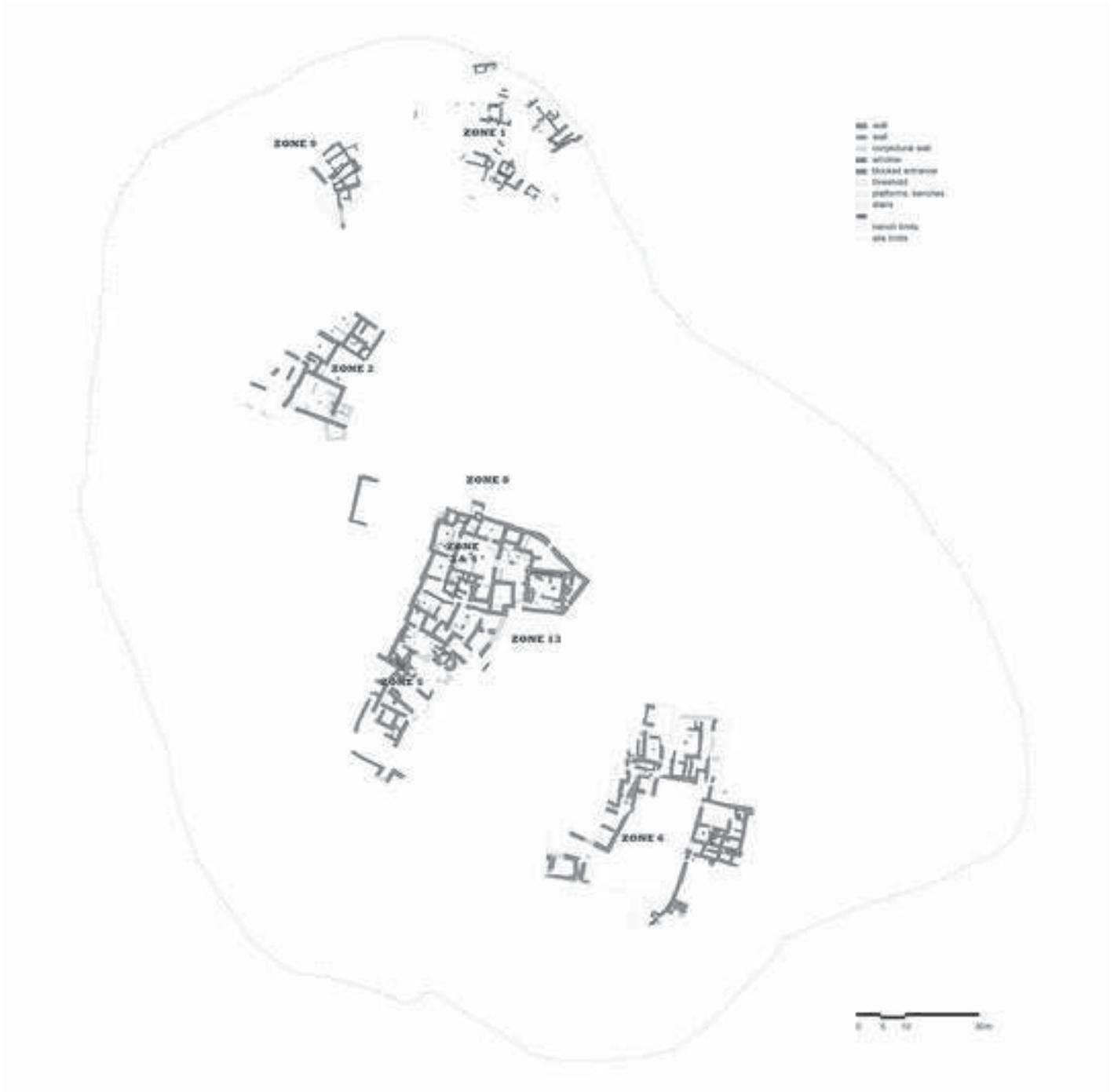
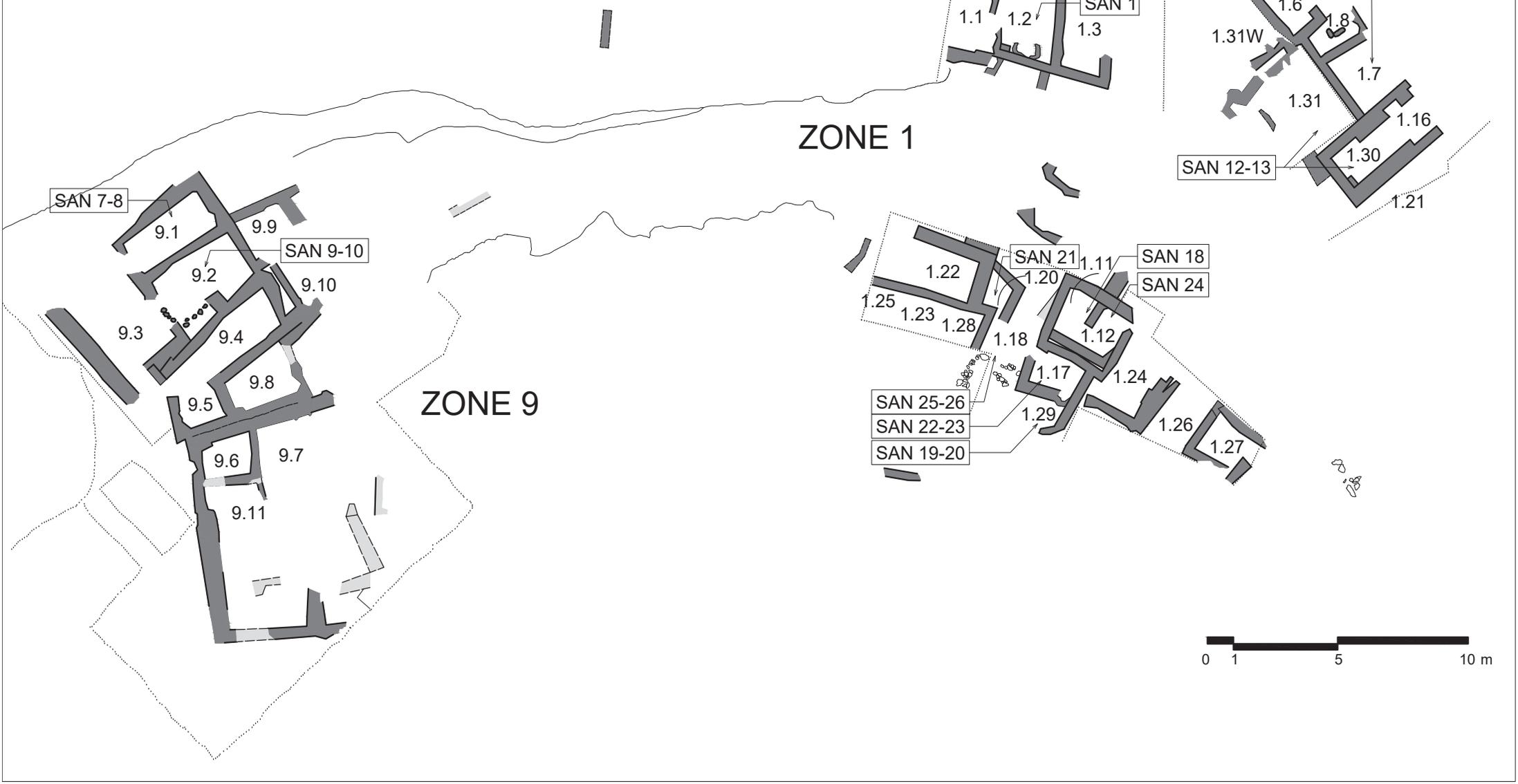
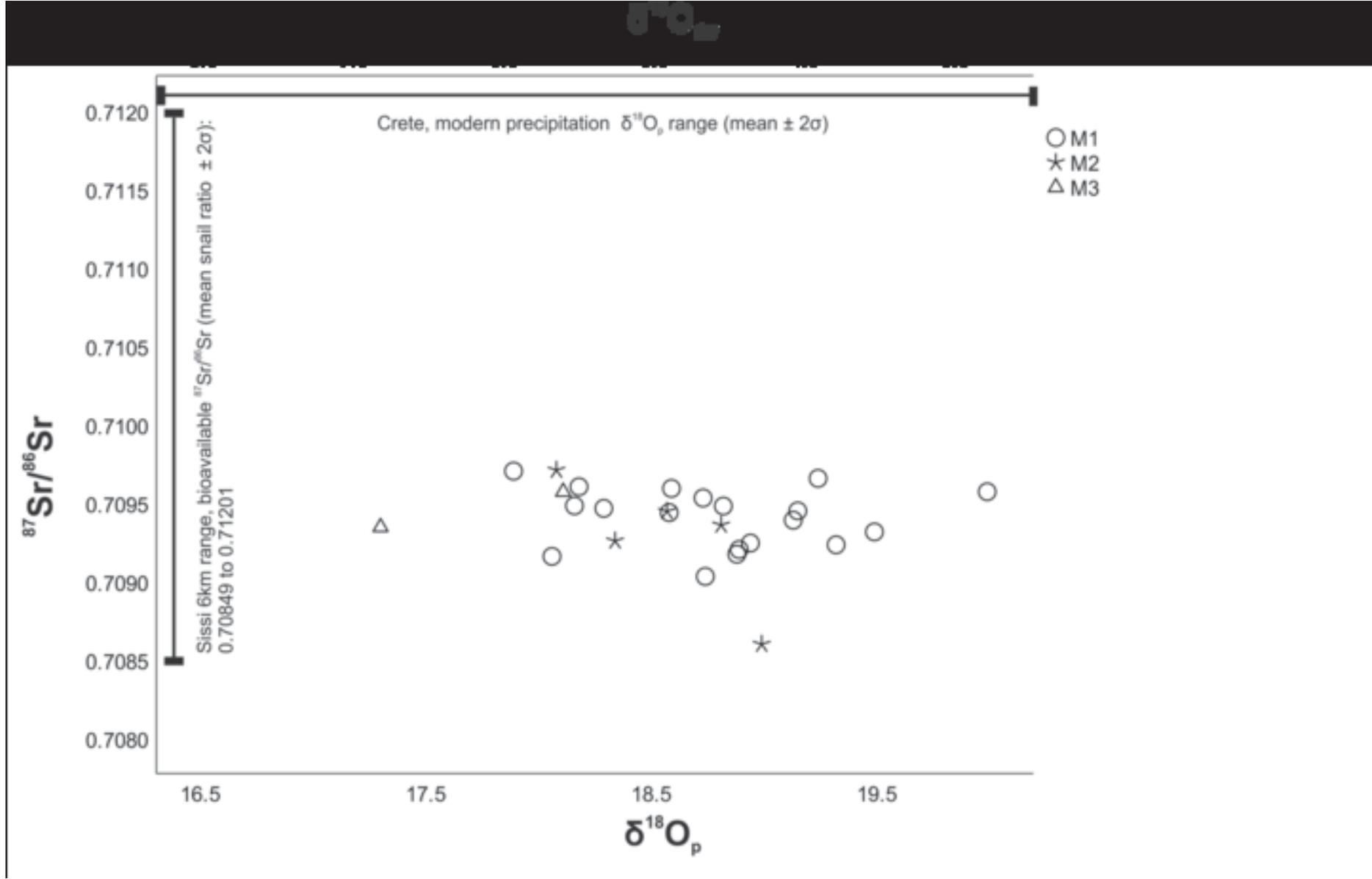


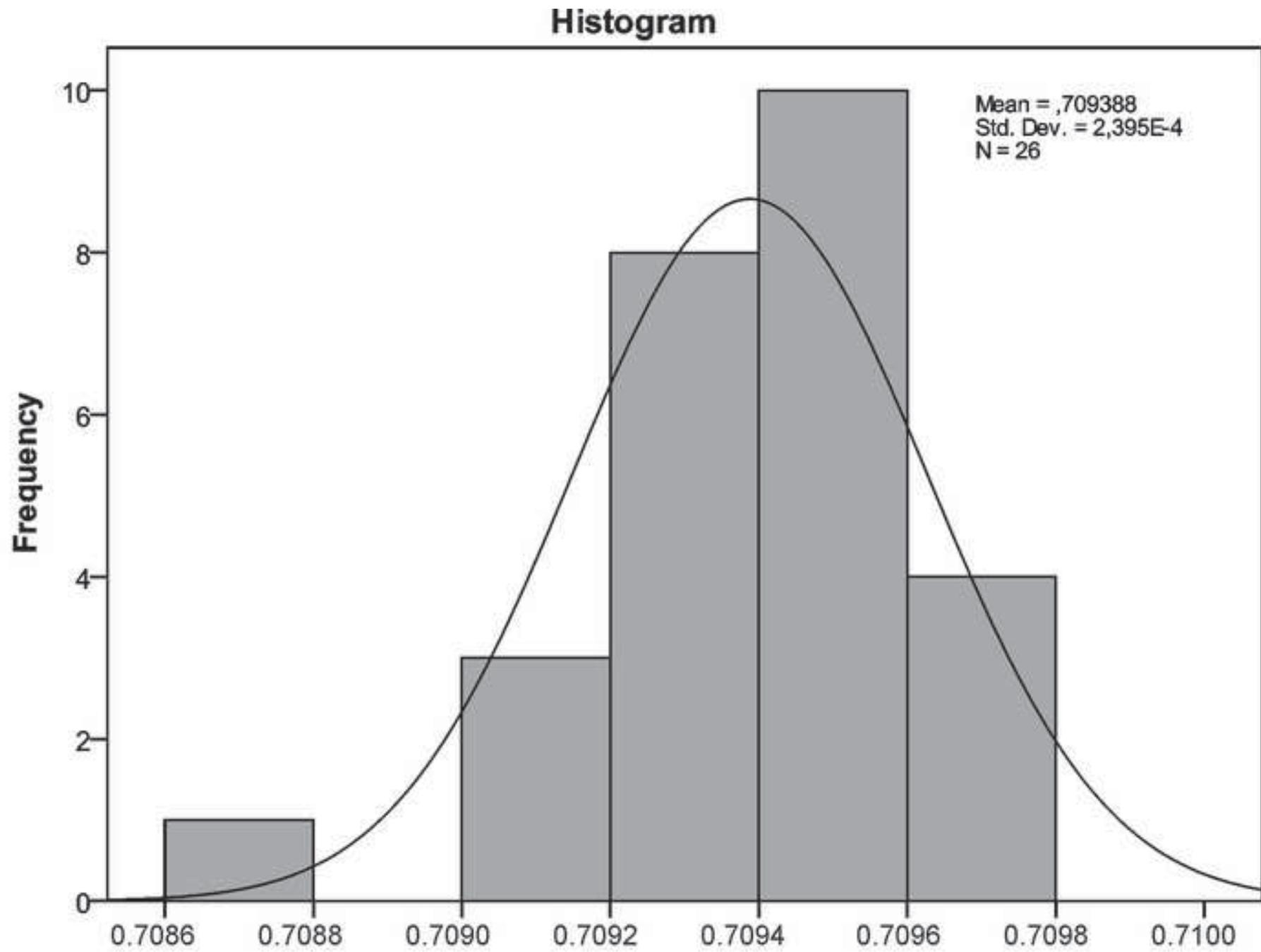
Figure 3

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

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







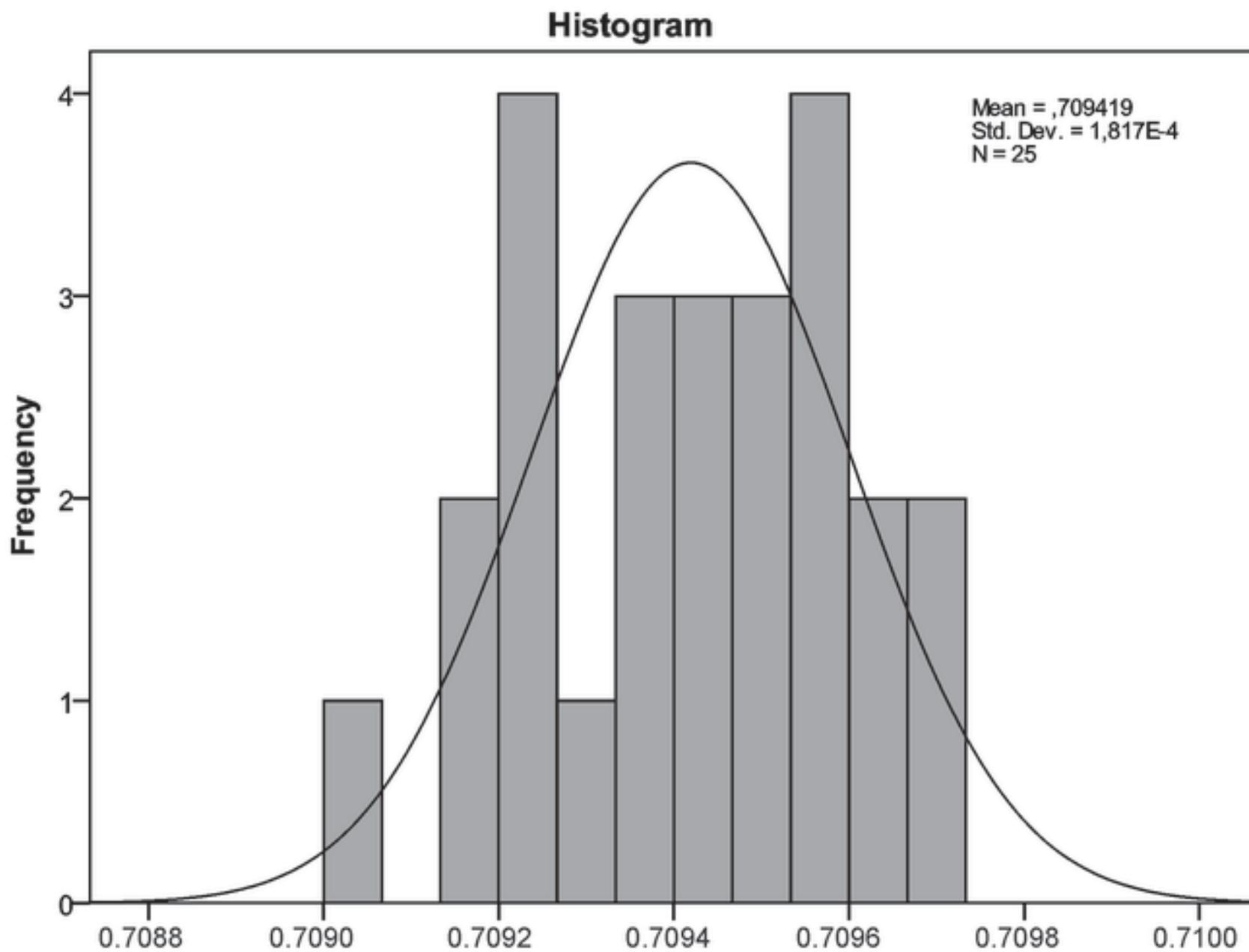
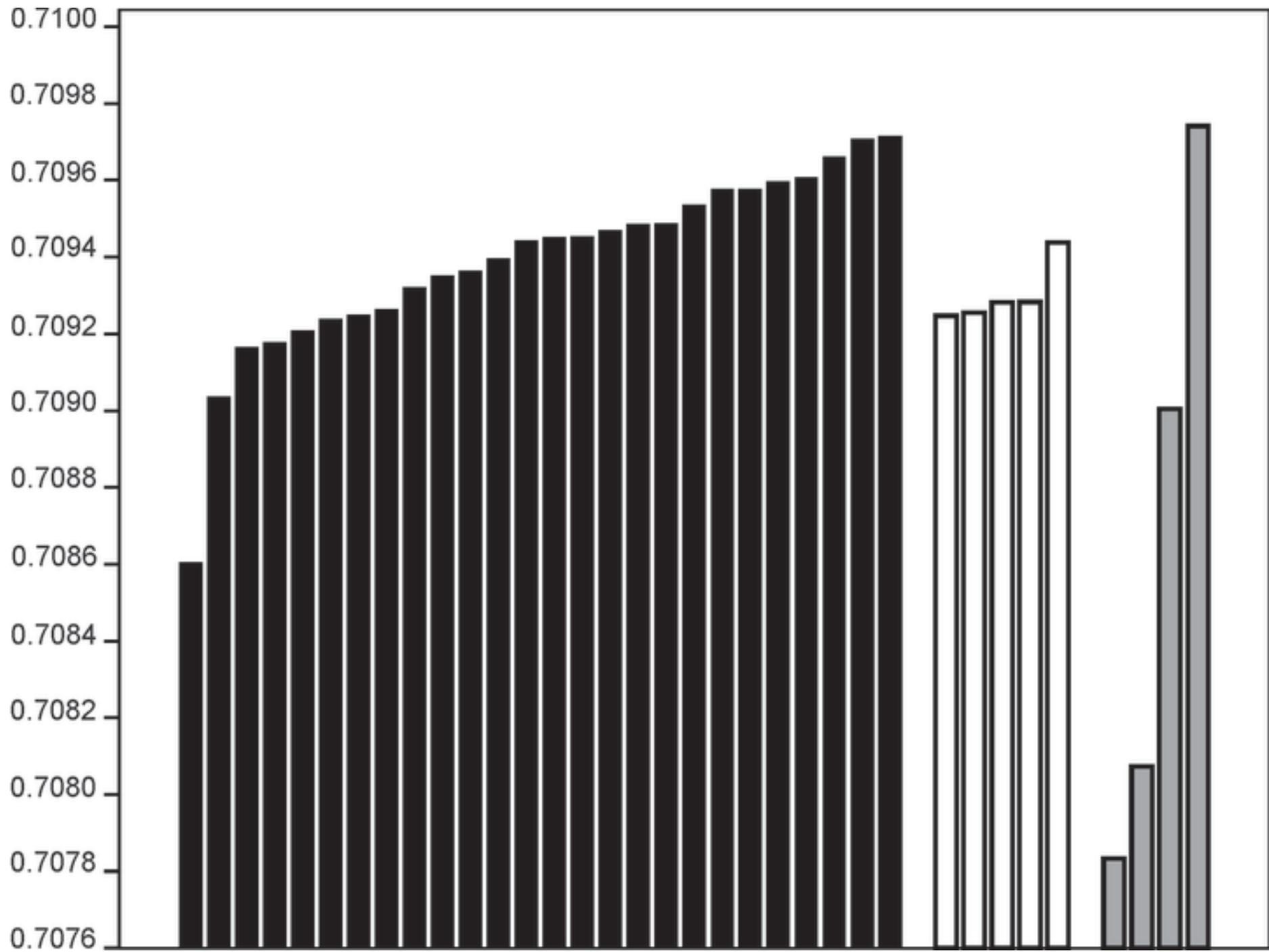
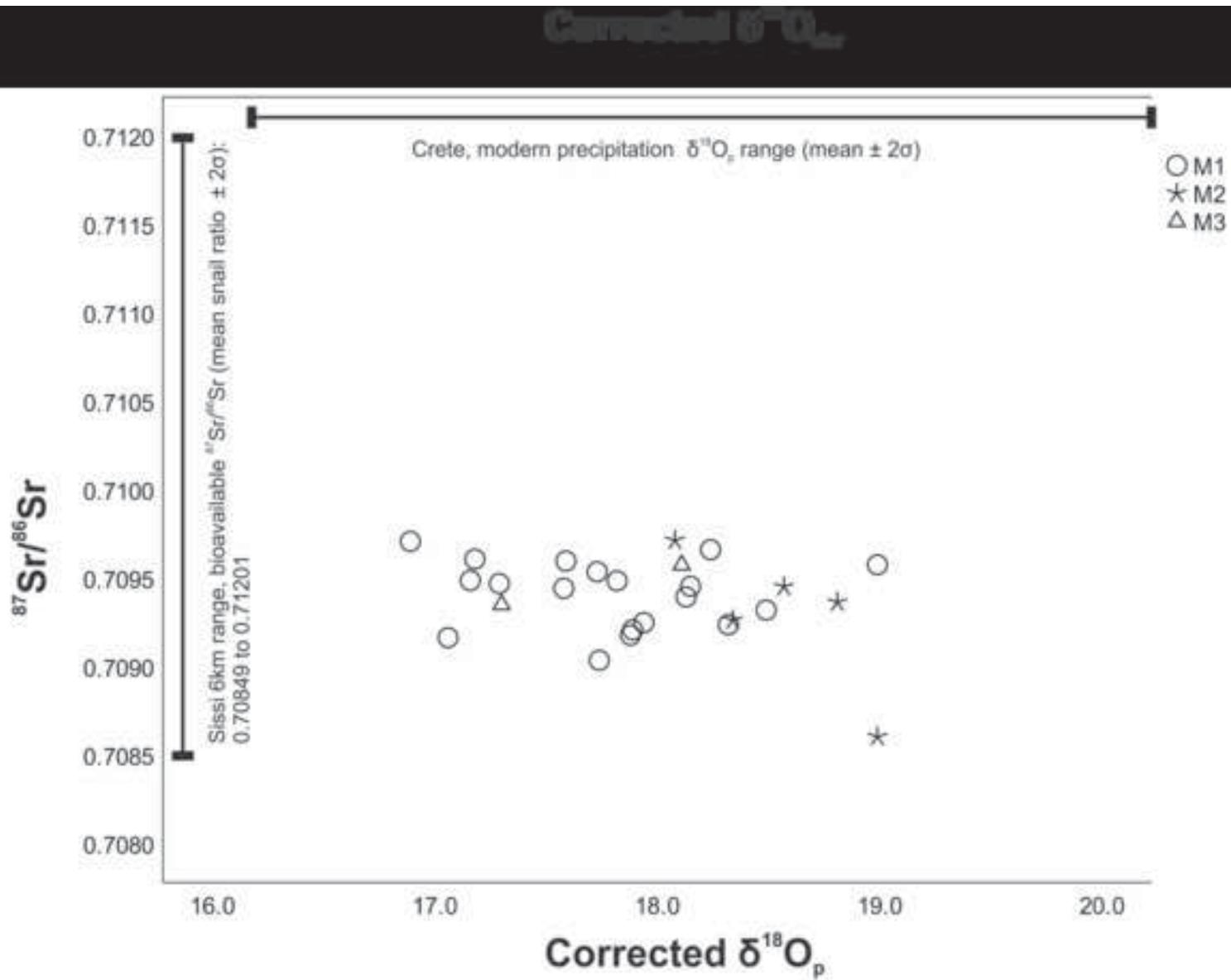


Figure 7





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Table

Table 1.docx



