Journal of Archaeological Science: Reports 35 (2021) 102718

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Mobile (after-)lifeways: People at pre- and protopalatial Sissi (Crete)

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ARTICLE INFO

Keywords:
Isotopes
Strontium
Oxygen
Provenance
Mobility
Diet
Land use
Settlement nucleation
Crete

ABSTRACT

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

Twenty-six human individuals from the site of Sissi were sampled for strontium and oxygen isotope ratio in tooth enamel, while five of them were also analysed for corresponding strontium isotope signatures in bone samples. The human tooth enamel strontium isotope signatures follow a broad distribution that is in overall agreement with the diverse substrate geology reported for the site and its immediate range within a radius of 5 km, as well as with strontium isotope results from snail samples also collected from the broader Sissi region. Strontium data variation can be explained by access to different feeding territories in close proximity to the site and possibly also as a result of variation in the composition of childhood diet, while some short-range immigration cannot be excluded either. In a fashion similar to the strontium data, the human oxygen isotope signatures are also consistent with a provenance from within the island.

Isotope data variation and the inferred maximization of the exploitation of arable land to extend the agricultural resource base is largely in tune with contemporary socio-economic developments, settlement nucleation and population growth on Crete towards the late Prepalatial period. Use of multiple production zones by the people at Sissi may also be seen as a buffer against climate instability and vulnerability of coastal sites, while settlement nucleation is supported by evidence for the abandonment of contemporary sites in the bay of Malia with the exception of Sissi and Malia.

Based on these data we conclude that mobility was part of the life of people at Sissi. They were either moving as part of their daily routine to exploit food resources, or in relation to settlement nucleation with some of them having moved to Sissi from nearby sites. It is also possible that people from nearby sites were buried in the Sissi cemetery. Owing to the overlapping strontium and oxygen isotope signatures in the context of this study, it is currently impossible to choose between the above three scenarios.

1. Introduction

Until 40 years ago, archaeologists largely relied on material culture alone to explore past population life-histories and used this evidence to investigate questions of provenance and mobility (e.g. Scull, 1995; Branigan, 1984; Mee, 1982; Mellart, 1975; Warren, 1973; Tringham, 1971; Caskey, 1960). Hence, on Early Bronze Age Crete (3rd millennium BCE), for example, diversity in mortuary behaviour as amply evidenced by funerary architecture and associated material culture and osteological records has led to inferences about the possible diverse origins of the people buried (Gkalanaki, 2020; Nafplioti, 2020, 2007; Legarra Herrero, 2009, 2014; Vavouranakis, 2007). Since the 1980s, however, initially in America and Northern Europe but later also in the rest of the globe, biogeochemical analysis of archaeological human skeletal remains has generated substantial new data on the lives of past people and helped shed new light onto long-standing questions of provenance and mobility, cultural discontinuity and change (e.g. Price et al., 2000; Ericson, 1985; van der Merwe, 1982; DeNiro and Epstein,

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https://doi.org/10.1016/j.jasrep.2020.102718
Received 13 May 2020; Received in revised form 19 October 2020; Accepted 12 November 2020

1981). In this paper, we use human skeletal remains from Early and Middle Bronze Age or Pre- and Protopalatial funerary contexts at Sissi on the north-east coast of Crete and employ for the first time on human remains from the island integrated oxygen and strontium isotope ratio analyses to offer a more nuanced understanding of past populations, their diets, potential origins and aspects of their mobility within the frame of regional socio-political developments (Fig. 1). The combined application of these two independent isotope systems, which serve as proxies for local geology and environmental conditions, respectively, enhances their potential for identifying newcomers and tracking past residential mobility compared to that of either system applied in isolation (Cavazzuti et al., 2019; Evans et al., 2019; Knipper et al., 2017; Killgrove and Montgomery, 2016; Chenery et al., 2010; Mitchell and Millard, 2009; Knudson and Price, 2007). A sample of 26 individuals was analyzed.

2. Background

2.1. Archaeological context

Excavations by a team of the UCLouvain under the auspices of the Belgian School at Athens have been taking place at the seaside promontory site of Sissi since 2007 (Driessen et al., 2018, 2012, 2011, 2009). In 10 campaigns, substantial parts of a cemetery, settlement and ceremonial building have been uncovered (Fig. 2). The site at Sissi is only c. 3 km to the east of the Bronze Age settlement at Malia (Fig. 3), where around 1900 BCE a large monumental complex, conventionally called a 'palace' in Cretan archaeology, was constructed (Driessen, 2010). On present evidence, both Malia and the site of Sissi were occupied from Early Minoan IIA (c. 2600 BCE) till the advanced Late Minoan IIIB period, the end of the Late Bronze Age (c. 1230 BCE). While Malia's prominent role in the region was undoubtedly connected to its agricultural hinterland, in the case of Sissi, the longevity of occupation can probably be explained by its advantageous strategic location. Situated

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

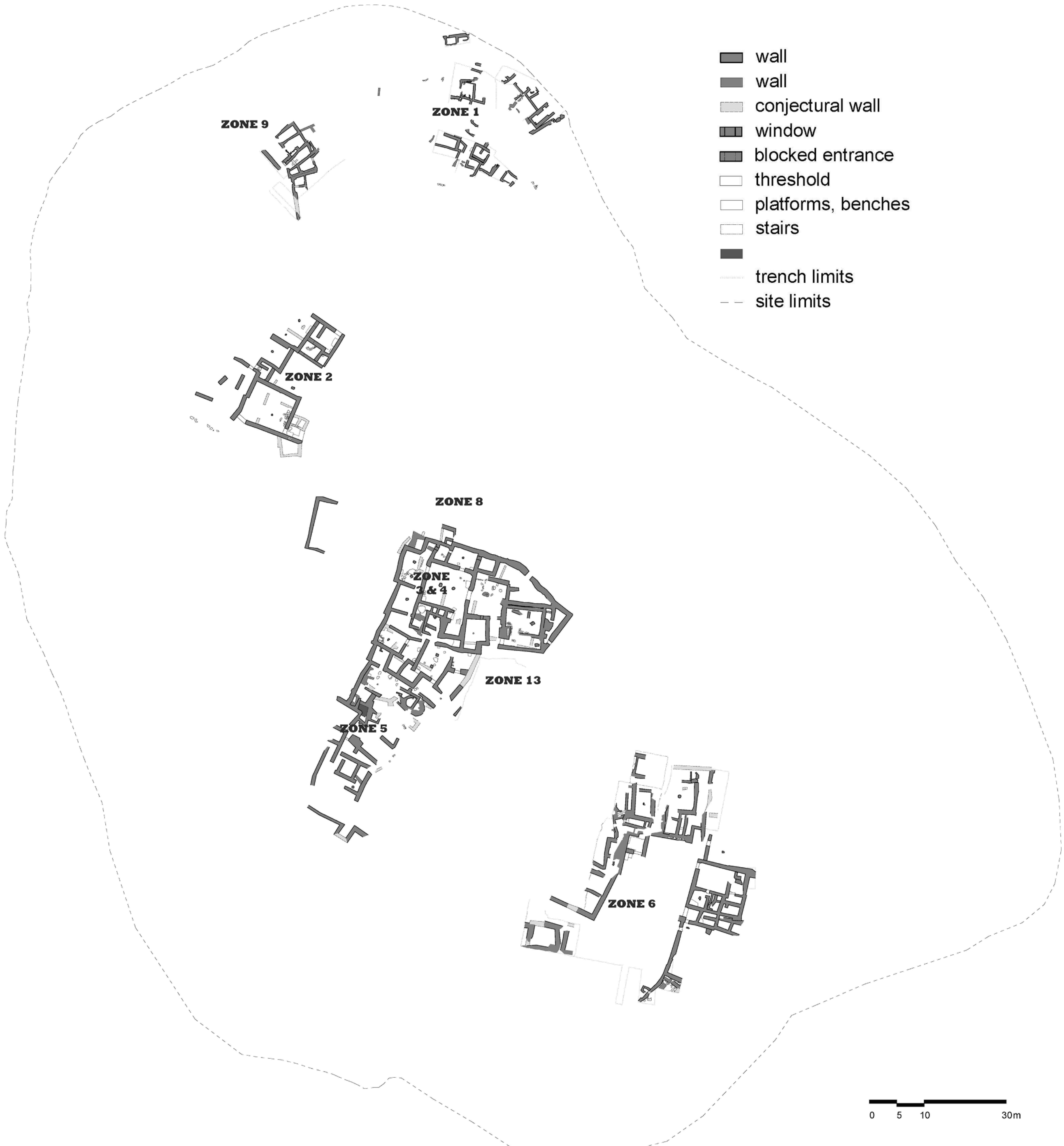

Fig. 2. Site plan of Bronze Age Sissi on Crete showing all zones excavated.

on a coastal hill with relatively steep sides and beaches on either side, the site is located opposite the Selinari Gorge, then and now the only route between Central and East Crete and an ideal communication artery, allowing interregional mobility. Within this paper, we are primarily interested in the Early and Middle Bronze Age occupation of the site (c. 2600–1750 BCE), the period during which the cemetery was in use.

During the Early Bronze Age (Early Minoan IIA, c. 2600 BCE, henceforth EM), a village was established on the summit of the Sissi hill. It formed, together with nearby Malia, one of a series of small Early Bronze Age hamlets that dotted the coast line and region (ca. 40 km^2) that extended from Stalidha to the west to Milatos to the east (Driessen, 2001; Müller-Celka, 2016). Both Malia and Sissi have yielded important architectural remains as well as other archaeological data (sealings, obsidian workshops, gold items) of the following, Early Minoan IIB period, allowing the suggestion that, at this particular time, the two settlements served as central places or hubs for the region, where people from the surrounding satellite sites may occasionally have congregated (Driessen, 2007). Most of these small satellite sites seem to have disappeared during the advanced Prepalatial Period (Early Minoan III-Middle Minoan IA, c. 2300–2000 BCE) and a settlement nucleation and a population contraction seems to have taken place with only Malia and Sissi continuing to be occupied. Moreover, only Malia and Sissi have cemeteries that continue to be used throughout the different phases

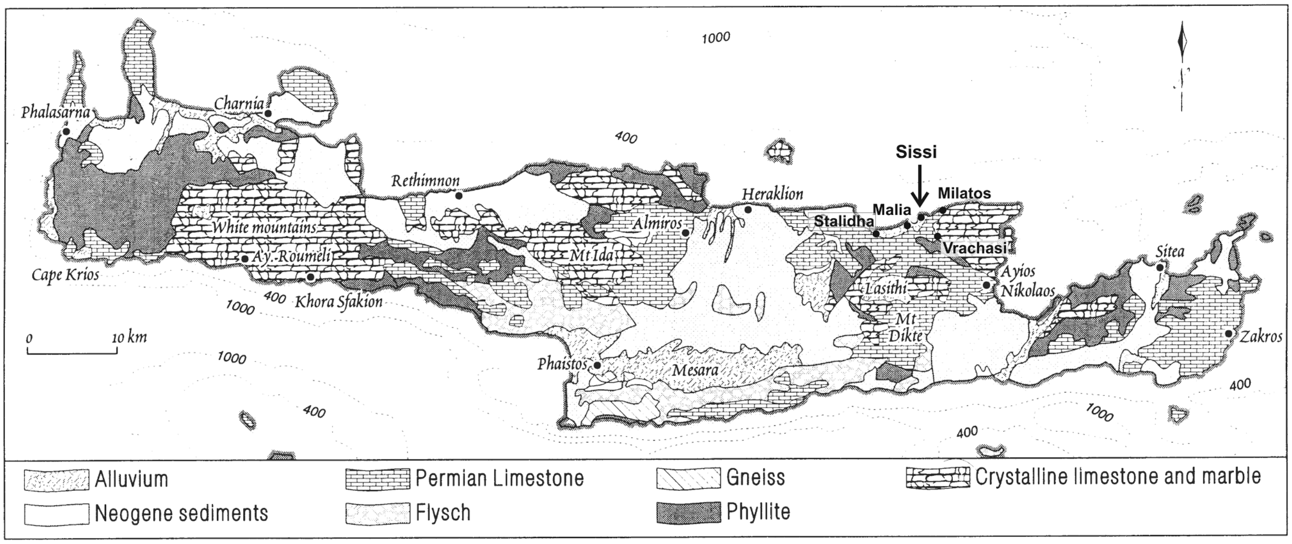

Fig. 3. Geological map Crete. After Higgins and Higgins (1996: Figure 16.1). Marked on it are the sites mentioned in the study.

(Legarra Herrero, 2014: 71, 74–75, 77–79). Afterwards, during the Protopalatial or Middle Bronze Age, however, dozens of smaller sites, mostly farmsteads, occupied the surrounding countryside. Within the coastal region that included 3000 ha of fertile land, Malia grew into the main urban and palatial centre (Müller-Celka, 2007, 2016; Müller-Celka et al., 2014), while the Sissi settlement seems to have continued at a smaller scale. Still, apart from Malia and Sissi and on present evidence, there are no signs of cemeteries elsewhere in the proximate region. The expansion of settlement into former non-occupied areas during the Middle Bronze Age will have impacted agricultural and land-holding practices in the surrounding territory (Whitelaw: 155, 2012; Whitelaw, 2019) and was accompanied at Malia by the construction of several public buildings.

From EM IIA onwards, the north side of the hill at Sissi housed a cemetery consisting a small stone buildings and compartments, known as House Tombs in Minoan archaeology (Schmitt and Sperandio, 2018; Crevecoeur et al., 2015; Schoep et al., 2012, 2011; Crevecoeur and Schmitt, 2009). Similar tombs have been excavated at Malia, Gournia, Mochlos, Petras and Palaikastro, for example, suggesting the presence of an especially East Cretan funerary tradition (Legarra Herrero, 2014). Other regions of the island followed other traditions, which could potentially imply a different cultural background and/or origins for the different communities. Although the House Tomb cemetery may have continued in use into the advanced Neopalatial period, at least where the higher terrace (Zone 18) is concerned, many buildings were ruined earlier and some of these ruins were used to insert pithos burials (Fig. 4) especially during the Middle Bronze Age (e.g. Schoep et al., 2012: 32–35). Although the bioarchaeological and chronological analyses are still ongoing, the published preliminary reports (Driessen et al., 2018, 2012, 2011, 2009) provide sufficient data to document and discuss the variability of strontium and oxygen isotope ratio values obtained from several individuals from the cemetery.

The 26 samples taken from skeletal remains for isotope analysis and presented in this paper come from burial structures that are located in various areas of the cemetery that spreads over three different terraces (Fig. 5). On the lowest terrace in the east part (Zone 1), one ossuary and a collective burial (Crevecoeur et al., 2015), Burial Buildings 1.9 and 1.10, were excavated, comprising respectively at least 11 and 20 individuals (Schoep et al., 2011: 64–66). From here come the five samples SAN 2 to 6. Further east, on a slightly higher first terrace, is a series of north-facing funerary buildings. While the plans of the spaces are relatively clear, there was not much earth deposition and erosion had taken its toll. Still, in some cases skeletal remains were sufficiently well

Fig. 4. Photograph of the individual primary burial of an adult male deposited in a pithos in the area 1.18 of zone 1 (© I. Crevecoeur).

preserved for sampling. From the higher, only partially excavated levels in spaces 1.30–31, a waste area resulting probably from tombs emptied, come samples SAN 12 and 13, while from the largest room, a collective burial 1.7, four samples were taken (SAN 14 to 17). On the second terrace, more to the west, one sample was taken in compartment 1.2 from Burial Building 1.1–1.3 (SAN 1). On the third and upper terrace, samples were taken both in the east part (Zone 1) and in the north zone of the cemetery (Zone 9), which is about 35 m to the west. In this north zone, there is a large Middle Minoan I-II Burial Building A (Schmitt and Sperandio, 2018) and from the first two excavated rooms 9.1–9.2 (Fig. 6), five samples (SAN 7 to 11) were taken. The west part of the east cemetery on the third terrace comprised a series of small stone compartments. The narrowness of the compartments and their bad preservation makes it difficult to discern a clear plan in the remains but from skeletal remains in one space (1.20) sample SAN 21 was taken. From skeletal remains in the corridor-like structure east (Fig. 4) two more samples were taken (SAN 25–26). The eastern part of this terrace has at its core an EM IIB Burial Building with two compartments (1.11 and

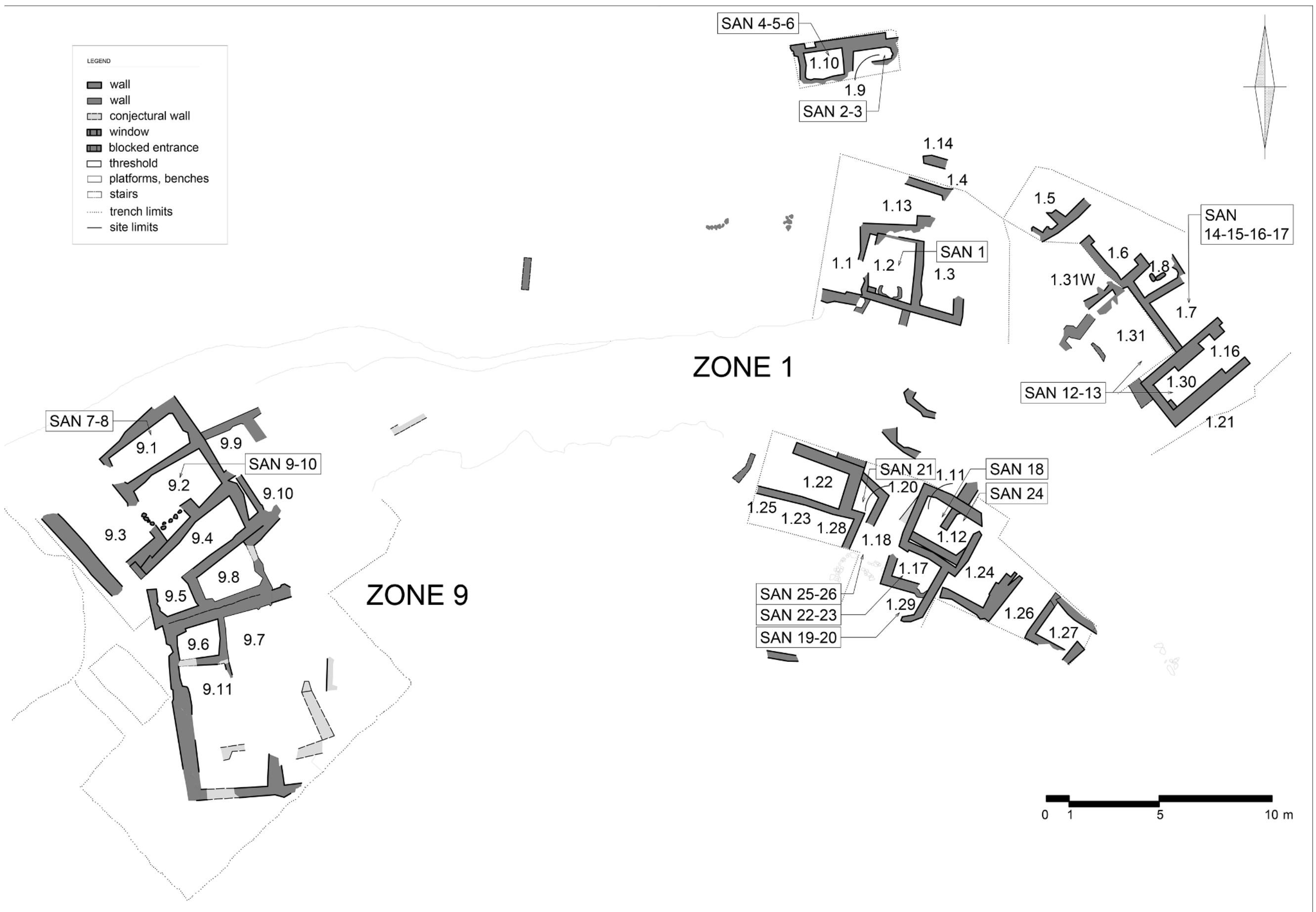

Fig. 5. Plan of the Pre- and Protopalatial cemetery at Sissi showing the locations where the samples analysed were recovered from (©EBSA, E. Zografou; edited by J. Driessen).

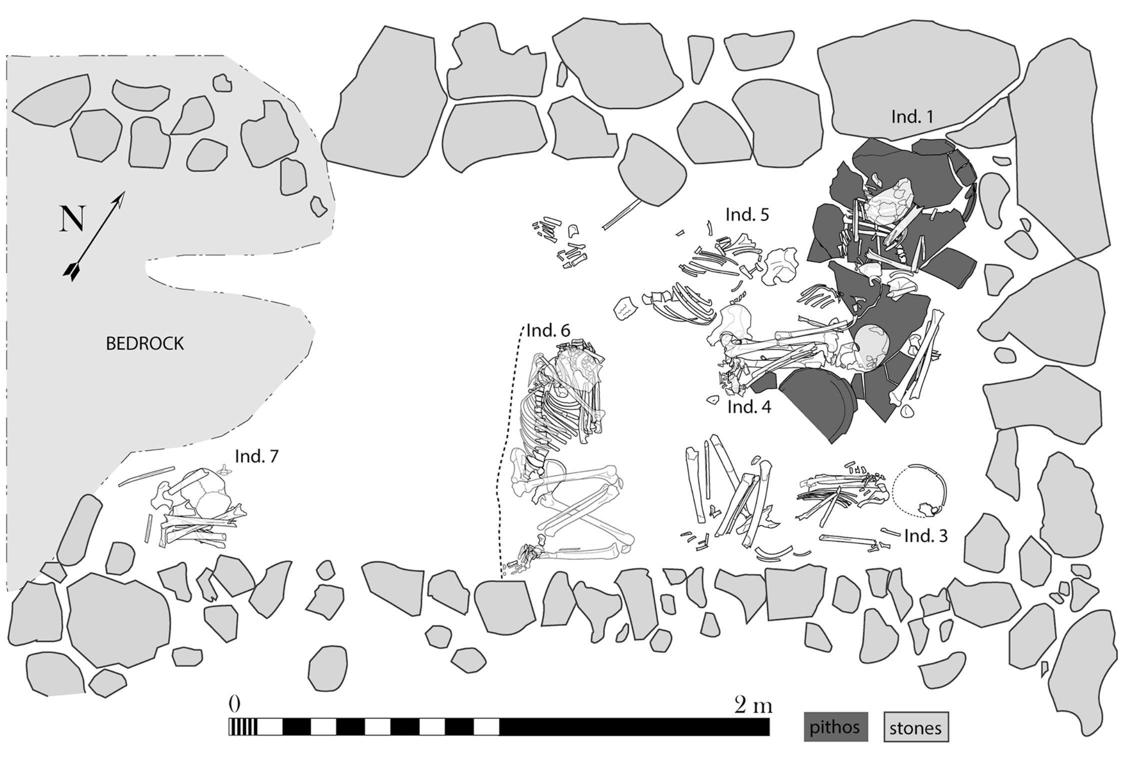

Fig. 6. Second funerary layer of the collective burial in room 9.1 (©EBSA; A. Schmitt).

1.12). Each room was sampled (SAN 18–24). This EM IIB tomb was partly overbuilt later and from this later room (space 1.17) we took two more samples (SAN 22–23). Two more samples were taken from a context (space 1.29) that is even at a higher level and probably even later (SAN 19–20). The human remains were covered by sediment to seal a funerary level or after the abandonment of the compartment. The method elaborated by Bruzek (2002) was applied to estimate sex of the skeletal remains. Since innominate bones were badly preserved, most of adults remain undetermined. Age-at-death was assessed by different methods according to skeletal maturation and growth of the individuals (Moorrees et al., 1963; Ubelaker, 1978; Scheuer and Black, 2000; Schmitt et al., 2002). The overall anthropological series include all sex and age categories. Perinates and young children are very well represented and seem to have had access to similar funerary treatment as adolescents and adults, which is a particularity of the site.

The plan in Fig. 5 shows that large parts of the cemetery were covered by this sampling, which can be considered as representative. Moreover, samples date from in between EM IIB to MM IIB (ca. 2500–1750 BCE), and may hence also provide a chronological representativity. Table 1 provides information on burial practices (individual or commingled remains) and the type of samples.

2.2. Strontium and oxygen isotope ratio analysis: principles

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

2.2.1. Strontium isotope ratio ($^{87}Sr/^{86}Sr$) analysis

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

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

In essence, $^{87}Sr/^{86}Sr$ largely reflects local geology, and passes from the bedrock into the soil, the groundwater and the food chain. Thereby $^{87}Sr/^{86}Sr$ reaches the human skeletal tissues, where it substitutes for calcium in hydroxyapatite (Faure, 1986), largely from the food and water consumed with no fractionation related to biological processes (Blum et al., 2000; Graustein, 1989). Although other factors such as proximity to marine environments and $^{87}Sr/^{86}Sr$ in sea spray (Veizer, 1989), atmospheric deposition (Miller et al., 1993) and in modern contexts fertilizers too (Thomsen and Andreasen, 2019; Bentley: 142, 2006; Graustein, 1989), can also impact on local $^{87}Sr/^{86}Sr$ signatures, the latter largely reflect bedrock geology and mineral weathering. Thus $^{87}Sr/^{86}Sr$ signatures in human skeletal tissues match the geochemical profile of the catchment area of the individuals analysed.

Because tooth enamel is a cell-free tissue that for most of the permanent dentition largely forms by the 8th year of life and does not remodel thereafter (Hillson, 2002; Ubelaker, 1989), $^{87}Sr/^{86}Sr$ signatures from tooth enamel reflect early childhood diet and geographical origins. Conversely, bone and, to a lesser extent, also dentine, undergo continuous replacement of their mineral phase in the course of life. In addition, tooth enamel is denser, harder and more inert than bone or dentine, and therefore more resistant to post-burial isotopic contamination than bone or dentine (Budd et al., 2000; Chiaradia et al., 2003; Hoppe et al., 2003; Kohn et al., 1999; Lee-Thorp and Sponheimer, 2003; Price et al., 1985). Thus cortical bone $^{87}Sr/^{86}Sr$ signatures more closely reflect the dietary intake of the last 10–20 years of life, and human bone $^{87}Sr/^{86}Sr$ values can be used to characterize local bioavailable $^{87}Sr/^{86}Sr$ at one's site of residence prior to death (Hedges et al., 2007; Manolagas, 2000; Nafplioti, 2008; Tafuri et al., 2006; Ezzo and Price, 2002; Ezzo et al., 1997; Grupe et al., 1997; Price et al., 1994).

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

2.2.2. Oxygen isotope ratio ($^{18}O/^{16}O$) analysis

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

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

Tooth enamel $^{18}O/^{16}O$ largely reflects the $^{18}O/^{16}O$ in drinking water and also water in foods consumed by the individual during childhood, when teeth are formed (Hillson, 2002), with some enrichment in ^{18}O owing to metabolic fractionation. Moreover, tooth enamel $^{18}O/^{16}O$

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

Context	Room or space	Sample name	Individuality/ commingled	Type of burial	Skeletal element	Sex	Age	$^{87}Sr/^{86}Sr$ Tooth enamel	$^{87}Sr/^{86}Sr$ Associated Bone	$\delta^{18}Oc$ VPD	$\delta^{18}Op$ VSMOW	$\delta^{18}Odw$
Sissi cemetery	1.2	SAN 1	Individual	Individual burial in pithos	ULM1	Female?	>40 years	0.709574	0.709282 (Femur left)	−2.09	19.99	−3.39
	1.9	SAN 2	Commingled	Ossuary	ULM1	Unknown	Young child	0.709393		−2.91	19.13	−4.66
	1.9	SAN 3	Commingled	Ossuary	LLM1	Unknown	10–14 years	0.709206		−3.13	18.89	−5.01
	1.10	SAN 4	Commingled	Collective burial	LLM1	Unknown	Mature adult	0.709706		−4.07	17.89	−6.47
	1.10	SAN 5	Commingled	Collective burial	LRM1	Unknown	Young child	0.709485		−3.82	18.16	−6.07
	1.10	SAN 6	Commingled	Collective burial	LLM1	Unknown	Infant	0.709236		−2.72	19.32	−4.38
	9.1	SAN 7	Individual	Collective burial	ULM2	Unknown	Mature adult	0.708602		−3.03	18.99	−4.86
	9.1	SAN 8	Individual	Collective burial	URM2	Male?	Mature adult	0.709450	0.709283 (Femur right)	−3.43	18.57	−5.48
	9.2	SAN 9	Individual	Collective burial	ULM1	Unknown	Mature adult	0.709176		−3.14	18.88	−5.02
	9.2	SAN 10	Individual	Collective burial	URM2	Unknown	Mature adult	0.709712	0.709255 (Radius right)	−3.89	18.08	−6.20
	9.2	SAN 11	Individual	Collective burial	URM1	Unknown	Mature adult	0.709606		−3.79	18.18	−6.04
	1/30–31	SAN 12	Commingled	Dump	ULM1	Unknown	Mature adult	0.709452		−2.88	19.15	−4.62
	1/30–31	SAN 13	Commingled	Dump	ULM1	Unknown	Adolescent/young adult	0.709468		−3.69	18.29	−5.89
	1.7	SAN 14	Individual	Collective burial	ULM2	Male?	>30 years	0.709362	0.709247 (Ulna right)	−3.20	18.81	−5.12
	1.7	SAN 15	Individual	Collective burial	URM1	Unknown	Young child	0.709318		−2.56	19.49	−4.13
	1.7	SAN 16	Individual	Collective burial	URM1	Unknown	Young child	0.709441		−3.42	18.58	−5.46
	1.7	SAN 17	Individual	Collective burial	URM2	Female?	Adolescent/young adult	0.709162		−3.91	18.06	−6.21
	1.11	SAN 18	Individual	COLLECTIVE burial	ULM2	Unknown	Mature adult	0.709595		−3.41	18.59	−5.44
	1.29	SAN 19	Individual	Individual burial in pithos	LRM1	Unknown	Young child	0.709034		−3.27	18.74	−5.23
	1.29	SAN 20	Individual	Individual burial in pithos	URM1	Unknown	Mature adult	0.709659		−2.80	19.24	−4.50
	1.20	SAN 21	Individual	Individual burial	LRM1	Unknown	Young child	0.709261		−3.65	18.34	−5.82
	1.17	SAN 22	Individual	Individual burial in pithos	URM3	Female?	>30 years	0.709574		−3.87	18.11	−6.15
	1.17	SAN 23	Commingled	Collective burial	URM1	Unknown	Mature adult	0.709483		−3.20	18.82	−5.12
	1.12	SAN 24	COMMINGLED	Collective burial	ULM3	Male?	>30 years	0.709349		−4.63	17.30	−7.34
	1.18 south	SAN 25	Individual	Individual burial in pithos	ULM1	Male?	>30 years	0.709247	0.709438 (Femur left)	−3.08	18.94	−4.93
	1.18 north	SAN 26	Individual	Individual burial in pithos	ULM1	Unknown	young child	0.709534		−3.28	18.73	−5.24
		SAN 33			Snail shell			0.709741				
Vrachasi		SAN 34			Snail shell			0.708074				
Vrachasi		SAN 35			Snail shell			0.707833				
Vrachasi		SAN 36			Snail shell			0.709004				

Key: ULM1 = upper left 1st molar, ULM2 = upper left 2nd molar, ULM3 = upper left 3rd molar, URM1 = upper right 1st molar, URM2 = upper right 2nd molar, URM3 = upper right 3rd molar, LLM1 = lower left 1st molar, LRM1 = lower right 1st molar.

values from teeth formed during the first few years of life, i.e. the incisors, canine and 1st molar, when the individuals were most probably (still) breastfeeding, are enriched in ^{18}O ($^{18}O/^{16}O$ values raised by ca. 1‰) compared to teeth that form following cessation of the breastfeeding, reflecting a trophic level effect (Wright and Schwarcz, 1998).

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

Moreover, owing to much overlap in human $^{18}O/^{16}O$ values from different locations across continents, identifying probable geographical origins on the basis of oxygen isotope analysis alone often is not possible (Lightfoot and O'Connell, 2016). Instead, the efficiency of oxygen isotopes for tracing the provenance of human skeletal remains is reinforced when combined with strontium and/or other isotope ratios such as isotopes of lead or sulphur, which serve as proxies for local geology rather than local environment (Evans et al., 2019; Madgwick et al., 2019; Redfern et al., 2016; Muldner et al., 2011; Turner et al., 2009).

2.3. Geological context

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

The archaeological site of Sissi on the north-east coast of the island is set on a narrow strip of alluvium (Fig. 3). Less than 1 km to its south and further west extend Jurassic to Eocene thick bedded to massive limestones and dolomites of tidal to shallow water origin. For a small part to its south, these rocks are interrupted by an outcrop of the "Phyllite –Quartzite series" that contains rocks of different age, origin and grade of metamorphism. These include Permo-Triassic shales, phyllites, quartzphyllites and quartzites. Upper Miocene to Lower Pliocene limestones extend immediately to the east of the site, while no >5 km further in the same direction occur older rocks, i.e. Jurassic to Eocene crystalline limestones with bands and nodules of chert (Creutzburg, 1977). The site of Sissi and its immediate periphery are thus characterized by high geological variability.

3. Materials and methods

3.1. Samples

Strontium and oxygen isotope ratios were measured from tooth enamel samples from 26 individuals from different chronological contexts and locations within the Sissi cemetery chosen to span the entire site. Five of them were also analysed for corresponding $^{87}Sr/^{86}Sr$ signatures in bone samples. The latter, including isotope ratio values from 4 snail shell samples from the archaeological site of Sissi and the nearby village of Vrachasi, situated approximately 6 km to its south, which were used to characterize local bioavailable $^{87}Sr/^{86}Sr$, are reported in Table 1.

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

For the purposes of $^{18}O/^{16}O$ analysis, we aimed for the second permanent molar (M2), because the M2 enamel is known to mineralize largely between the age of seven and eight (Scheuer and Black, 2000; Ubelaker, 1989) and therefore the measured $^{18}O/^{16}O$ signatures are not expected to be affected by the consumption of mother's milk. This is known as the 'breastfeeding effect' where the oxygen isotope signal of enamel that mineralised during breastfeeding is raised by up to 1‰ over that of later forming teeth, reflecting the fact that nursing infants are feeding at a higher trophic level than their mothers (Hillson, 2002; Hoppe et al., 2003; Jay et al., 2008; Montgomery, 2002; White et al., 2000; Wright and Schwarcz, 1998). Where the M2 could not be sampled, it was substituted by the first (M1) or the third molar (M3), in eighteen and two cases, respectively, and this will be taken into account in the discussion and interpretation of the results.

3.2. Sample preparation and analysis

3.2.1. Strontium isotope ratio analysis

The analytical protocol for $^{87}Sr/^{86}Sr$ analysis, including procedures of sample extraction and sample preparation prior to analysis, have been detailed in earlier publications (Nafplioti, 2008, 2009a, 2009b, 2011). Samples of tooth enamel, bone and shell (>20 mg) were placed in the ultrasonic bath for a total of 30 min to remover surface contamination. The bath was interrupted every 10 min and the specimens were mechanically cleaned using ultrapure water (18.2 Ω). In order to remove diagenetic strontium, tooth enamel samples were leached in 2 ml of 5% acetic acid. Bone and shell samples were leached in 2 ml of 2% acetic acid. All samples were rinsed in ultrapure water (4 times) after the first hour of bathing in acetic acid and then placed back in fresh 5% and 2% acetic acid, respectively, and left overnight.

In the following day, samples were rinsed four times and dried in an oven (≤50 °C). All leachates were retained. Strontium columns were prepared by filling small Teflon columns up to the neck with cleaned Sr resin. The columns were cleaned with 3 ml H_2O and 3 ml of SB 3 M HNO_3. The matrix and everything except Sr and Rb was eluted with 2.5 ml of SB 3 M HNO_3. Sr was collected by passing ultrapure water and dried down on a hotplate. The Sr fractions were loaded onto single tantalum filaments with Ta-activator and the $^{87}Sr/^{86}Sr$ values were measured to the sixth decimal digit by a ThermoFisher TRITON Plus Thermal Ionization Mass Spectrometer (7 Collectors). Preparation and analysis of the samples had been carried out at the National Oceanography Centre in Southampton (NOCS).

3.2.2. Oxygen isotope ratio analysis

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

Following abrasion of the external tooth crown enamel surface using a dremel tool, enamel powder of approximately 8–12 μg was drilled out from the entire crown height avoiding to sample any adhering dentine. Enamel powders were then treated for bioapatite extraction following Balasse et al. (2002). After soaking samples in sodium hypochlorite 2–3% (24 h at 4 °C) to remove organic matter, the samples were rinsed five times in distilled water and mixed with 0.1 M acetic acid (0.1 ml/mg) for four hours at room temperature to remove exogenous carbonate. Following five rinses the samples were placed in the freezer at −20 °C for 1 h, and then at −80 °C for an additional 30 min before being freeze dried for 90 min. The dried samples were then transferred into suitable tubes and placed into a VG SIRA mass spectrometer, where each sample was reacted with 100% ortho phosphoric acid at 70 °C. Liberated CO2 was then trapped and transferred to the mass spectrometer for the isotopic analysis. Results are reported with reference to the international standard VPDB calibrated through the NBS19 standard (Hoefs, 1997; Coplen, 1995) in standard delta (δ) notation relative to the VPDB international standard and are expressed in units per mil (‰), i.e. $\delta^{18}O = 1000 \times [(^{18}O/^{16}O\ sample)/(^{18}O/^{16}OVPDB) - 1$, (Table 1).

All oxygen isotope ratio measurements including sample preparation were carried out at the McDonald Institute for Archaeological Research, University of Cambridge. The long term analytical precision is better than ±0.08‰ for $^{13}C/^{12}C$ and better than ±0.10‰ for $^{18}O/^{16}O$. The $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ project data were statistically analysed using IBM SPSS Statistics 25.

4. Results

Strontium and oxygen isotope ratio results from the 26 individuals from Sissi analysed are displayed in Table 1 and Figs. 10 and 11.

The human tooth enamel strontium isotope ratios range between 0.70860 and 0.70971 (mean: 0.70939, 0.00048 2σ) (Table 1, Figs. 7, 10 and 11). Variation is high, evidenced by the large standard deviation and range (Table 2). It is higher than other Bronze Age human skeletal collections in the South Aegean, viz. the Grave Circle A at Mycenae (2σ = 0.00004, N = 11), the Ailias (2σ = 0.00020, N = 8), Gypsades (2σ = 0.00006, N = 9), and Sellopoulo (2σ = 0.00030, N = 12) collections from Knossos, but lower compared with Manika on Euboea (2σ = 0.00130, N = 65) and the Chora of Naxos (2σ = 0.00088) (Nafplioti, 2007, 2008, 2009a, 2009b, 2012b, 2015).

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

Oxygen isotope ratios from tooth enamel carbonate from the same individuals yielded $\delta^{18}O_c$ values which are reported relative to the VPDB international standard. In order to facilitate comparison of the human $\delta^{18}O_c$ values to local precipitation data from the region and further explore provenance for the respective individuals we converted the carbonate oxygen VPDB data to carbonate oxygen VSMOW values using

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

Statistic	Complete	Trimmed
Mean	0.70939	0.70942
Median	0.70945	0.70945
Count	26	25
Std. Deviation	0.00024	0.00018
Minimum	0.708602	0.709034
Maximum	0.709712	0.709712
Range	0.001110	0.000678
Interquartile Range (IQR)	0.00033	0.00032
Skewness (standard error)	−1.39 (0.46)	−0.24 (0.46)
Kurtosis (standard error)	3.37(0.89)	−0.68 (0.90)
Shapiro-Wilk test (p value)	0.019	0. 739

the equation below (1)

$$\delta^{18}O\ VSMOW = (1.0309 \times \delta 18OVPDB) + 30.9 \quad (1)$$

(Friedman and O'Neil, 1977; Henton et al., 2010)

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

$$\text{If } \delta^{18}O_{mw} = 1.54\ (\pm 0.09) \times \delta^{18}O_p - 33.72\ (\pm 1.51) \quad (2)$$

Daux et al. (2008) and

$$\delta^{18}O_p = 0.98 \times \delta^{18}O_c - 8.5 \quad (3)$$

(Iacumin et al., 1996). Then

$$\delta^{18}O_{mw} = 1.51 \times \delta^{18}O_c - 46.81$$

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

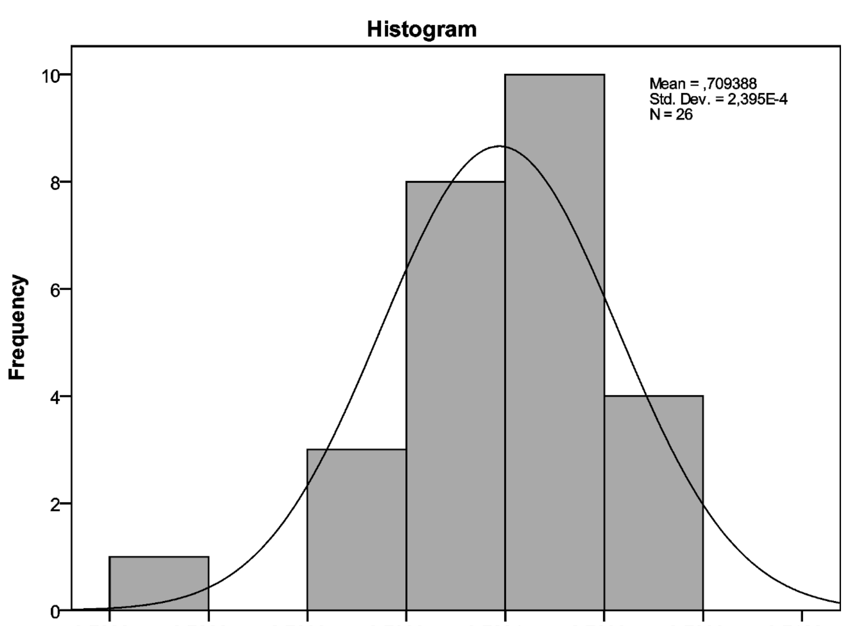

Fig. 7. Histogram of the complete Sissi human enamel $^{87}Sr/^{86}Sr$ data set, with normal distribution curve for comparison.

As was observed from the $^{87}Sr/^{86}Sr$ human tooth enamel data, the $\delta^{18}Op$ values from the same individuals follow a rather broad distribution, from 17.3‰ to 19.9‰ (mean 18.7 ± 1.2‰, 2σ) with corresponding drinking water values between −7.3‰ and −3.4‰ (mean −5.3 ± 1.7‰, 2σ) (Table 1, Fig. 10).

5. Discussion

5.1. Variation in strontium isotope ratios

Skeletal $^{87}Sr/^{86}Sr$ values from people, who were born and raised locally, and largely consumed local water and foods grown on the same soils, are expected to be normally distributed. Regardless what the actual soil values from the site under investigation and their associated food and water signatures are, averaging them through the human diet would result in a rather homogeneous set of human skeletal $^{87}Sr/^{86}Sr$ signatures. Thus for a local population, who largely lived on locally-grown or locally-procured food and water resources and were not appreciably mobile, tooth enamel $^{87}Sr/^{86}Sr$ signatures are expected to be normally distributed. In the absence of mobility, any variation in tooth enamel $^{87}Sr/^{86}Sr$ signatures between individuals from the same site will largely reflect differences in the relative contribution of foodstuffs of different $^{87}Sr/^{86}Sr$ signatures. The local territory of Sissi, which in the period examined is one of a series of small villages that dotted the north coast of the island between Stalidha to Milatos, located within less than 10 km to the west and east of the site, respectively, probably extended within a radius of 5 km.

Descriptive statistics were applied to the Sissi human tooth enamel $^{87}Sr/^{86}Sr$ data to explore whether they follow a normal distribution. The results suggest that the distribution of the data significantly differs from a normal one (Shapiro-Wilk Test: $p = 0.019$) (Table 2). Distribution of the $^{87}Sr/^{86}Sr$ signatures is leptokurtic, i.e. it has a positive kurtosis, and it is also skewed towards values higher than the mean, resulting in a median that is higher than the mean. The above are illustrated in Fig. 7, where an estimated normal distribution curve is also plotted for comparative purposes. The enamel $^{87}Sr/^{86}Sr$ value of 0.70860 (SAN7) lays >2σ away from the mean $^{87}Sr/^{86}Sr$ of the Sissi assemblage, and thus stands out at the left tail of the distribution curve as a possible outlier, i.e. a non-local at Sissi. This value was also identified as an outlier based on the 1.5IQR method, which is more robust to outliers (Table 2). When this outlier is eliminated from the dataset, the now trimmed data appear to follow a normal distribution (Shapiro-Wilk Test: $p = 0.739$); intra-group variation is lower (2σ = 0.00036) compared to the complete data set; mean (0.70942) and median (0.70945) are closer (Table 2, Fig. 8).

Albeit not statistically justified, additional values at the tails of the distribution may also indicate non-locals at Sissi, or people who moved at Sissi when they were very young, i.e. while tooth enamel for the permanent dentition was still forming (Fig. 8). Nonetheless, it is not clear where exactly in the distribution one should safely draw the boundaries for the local Sissi population. In the following, data on the local biologically available $^{87}Sr/^{86}Sr$ on the one hand, and information on the local geology and the site's distance from the sea on the other, may prove useful in this respect.

Fig. 9 plots the human tooth enamel and bone $^{87}Sr/^{86}Sr$ signatures together with data on the local biologically available $^{87}Sr/^{86}Sr$ measured from snail shells from the site and the broader region. The human cortical bone values reflect adult diet during the last 10–20 years or so in one's life and follow a narrower distribution than the tooth enamel ratios. This is not surprising as tooth enamel ratios reflect a much narrower period, i.e. a maximum of 2 to 3 years in early childhood. Additionally, bone is more susceptible to post-depositional contamination, which would potentially narrow isotope ratio variation down to the isotope ratio signatures of the burial environment. Bone isotope signatures are also less variable than the ratios measured from the snail shells.

Snail shell $^{87}Sr/^{86}Sr$ values are in good agreement with the highly variegated substrate geology for the broader Sissi region where limestones of different age and old metamorphic rocks occur in a radius of just 5 km, as described in Section (2.3) above. Intra-group variation (2σ = 0.00176) for the four snail samples is higher compared to the human enamel values, while the actual values range between 0.70783 and 0.70974. The latter was measured from a specimen collected from the excavation site, while the remainder three $^{87}Sr/^{86}Sr$ shell values average at 0.70830 ± 0.00062 and were measured from the three Vrachasi village snails. All 26 human enamel ratios in fact fall within the range of the snail ratios and can therefore be identified as locals within the broader region of Sissi (Figs. 10 and 11).

If we look carefully at the Sissi human enamel $^{87}Sr/^{86}Sr$ data, these generally fit provenance in coastal areas where marine strontium from seaspray, rainwater and shell sands have a significant impact on the

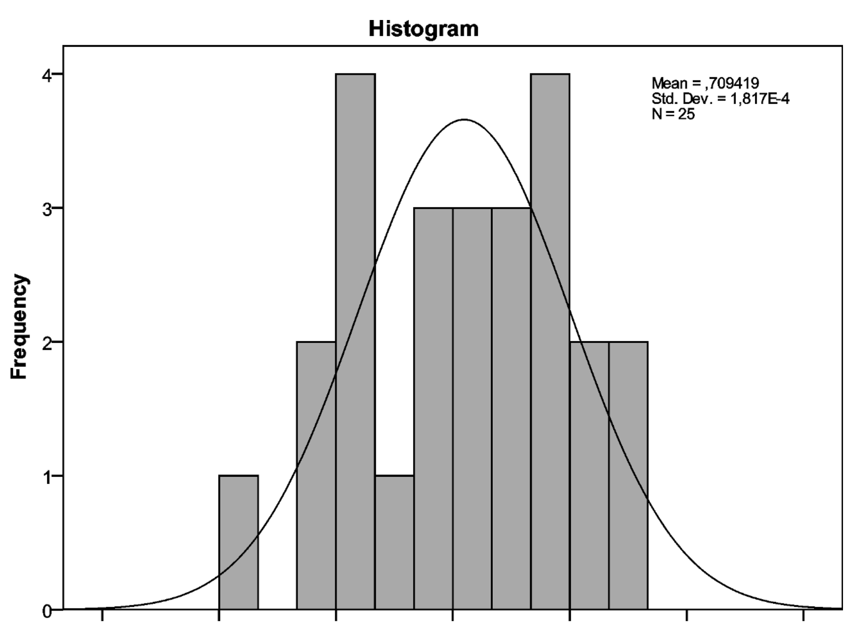

Fig. 8. Histogram of the trimmed Sissi human enamel $^{87}Sr/^{86}Sr$ data set, with normal distribution curve for comparison.

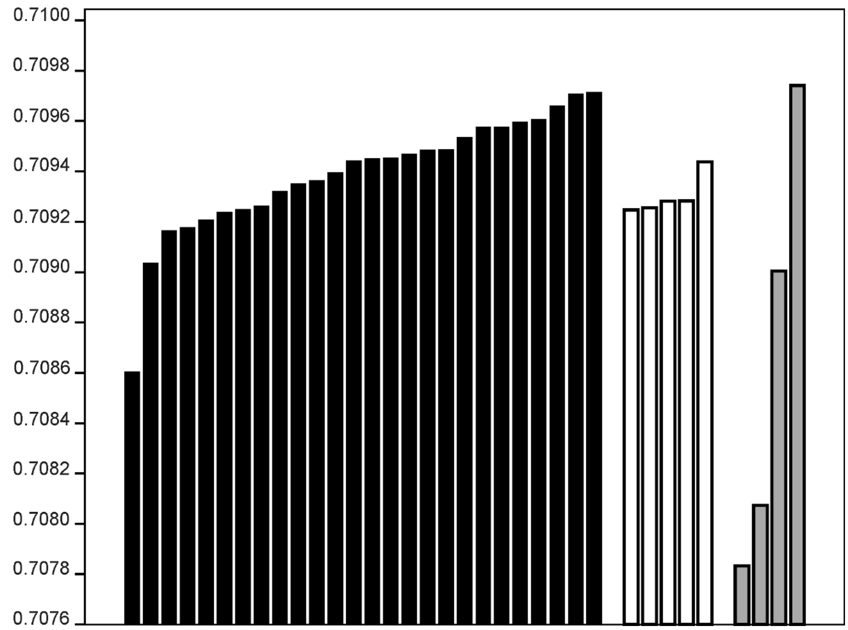

Fig. 9. Strontium isotope ratio ($^{87}Sr/^{86}Sr$) values from human enamel samples from Sissi and snail shell values from the broader region. Key: BARS: black = human dental enamel, white = human bone, grey = snail shell.

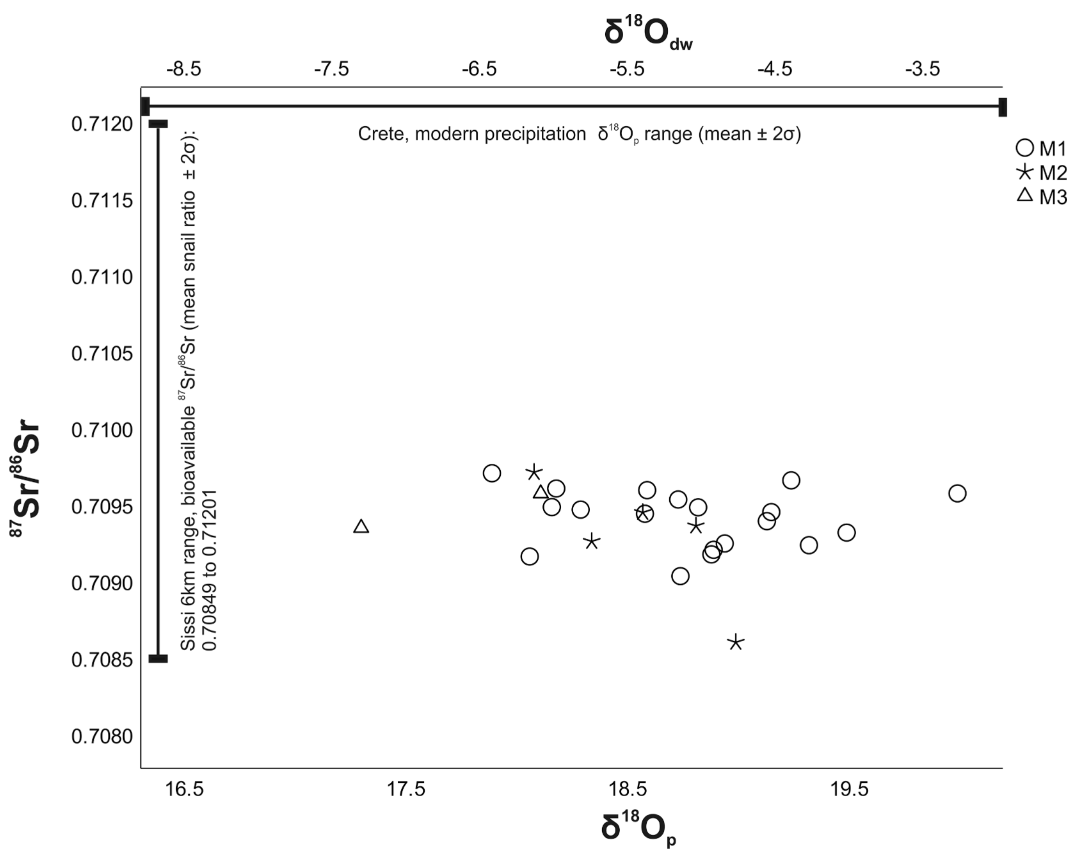

Fig. 10. Strontium and oxygen (phosphate and calculated drinking water values) isotope ratios for individuals from Sissi. The circle denotes samples from M1s which are probably affected by the breastfeeding effect. The star and triangle mark M2s and M3s, respectively, which form after individuals were weaned. Shown on the graph are the estimated range of bioavailable $^{87}Sr/^{86}Sr$ 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).

local biosphere Sr values, i.e. around 0.7090–0.7092 (Montgomery et al., 2007, 2003; Bentley: 153, 2006; Veizer, 1989). Nonetheless, the $^{87}Sr/^{86}Sr$ value of 0.70860 from individual SAN7, who was statistically identified as an outlier, falls below the modern seawater $^{87}Sr/^{86}Sr$ constant of 0.7092 (Veizer, 1989). Albeit not compatible with an origin from a coastal site, the $^{87}Sr/^{86}Sr$ value from SAN7 does not exclude an

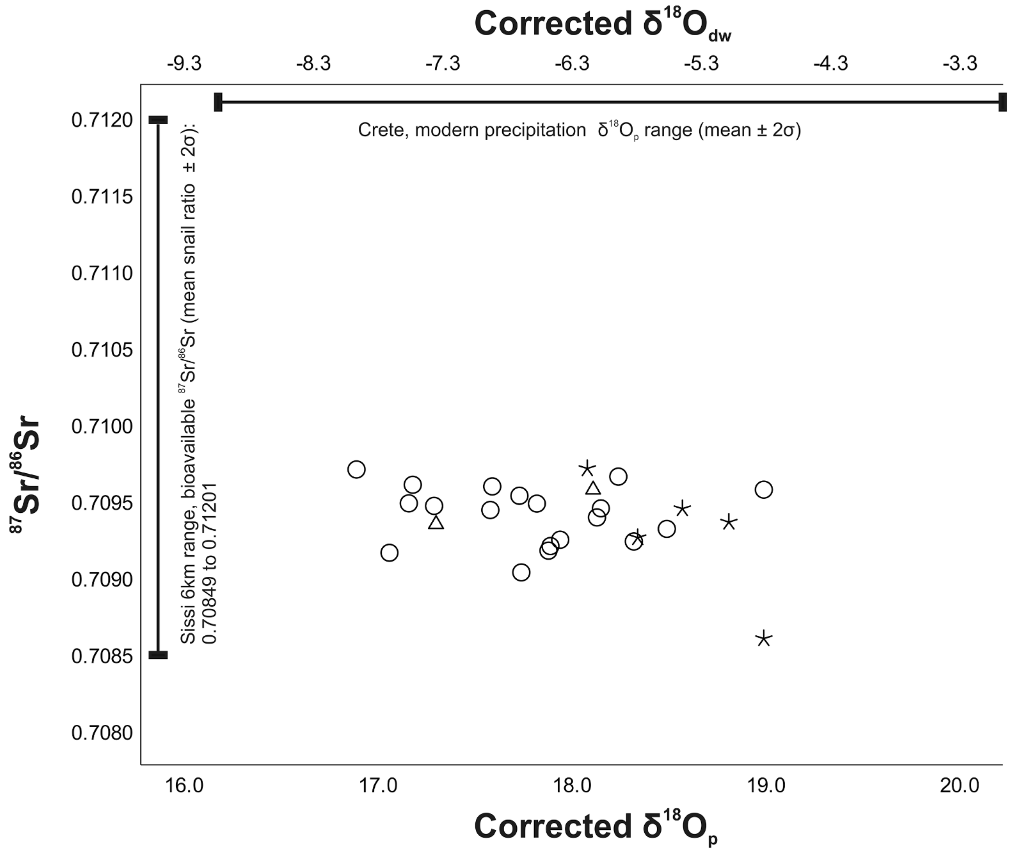

Fig. 11. Strontium and corrected oxygen (phosphate and calculated drinking water values) isotope ratios for individuals from Sissi. The circle denotes oxygen values from M1s corrected for a potential breastfeeding effect, while the star and triangle mark M2s and M3s, respectively, which form after individuals were weaned.

origin within the island. Strontium isotope ratios similar to SAN7 from Burial Building 9.1, although rare amongst the local bioavailable $^{87}Sr/^{86}Sr$ signatures from Crete, are not altogether absent. In fact, the two lowest $^{87}Sr/^{86}Sr$ signatures from the Vrachasi snails measured as 0.70783 and 0.70807 suggest that it would not be illegitimate to infer that SAN7 was local at the broader Sissi region. Similarly low isotope values from the rest of the island, including a published value of 0.70853 measured from a sheep/goat from Bronze Age Knossos (Nafplioti, 2011: 1564, 1567), as well as more data currently under preparation for publication (Nafplioti, in preparation), further corroborate a provenance within the island for the individuals in question. An additional three low human enamel $^{87}Sr/^{86}Sr$ signatures were recorded from south-east Crete (Triantaphyllou et al., 2015), however these data should be treated with caution due to the very low sample size and the lack of associated bioavailable strontium ratio background data from that region.

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

In the context of high variation in the underlying geology of the region, the more radiogenic enamel $^{87}Sr/^{86}Sr$ signatures probably reflect older geological formations and different catchment areas for the respective individuals compared to burials with lower $^{87}Sr/^{86}Sr$ signatures that are close to the seawater $^{87}Sr/^{86}Sr$ constant. The human enamel $^{87}Sr/^{86}Sr$ results of the individuals buried in the Sissi cemetery throughout the different phases therefore seem to be consistent with extensification of land use during this period and access to different feeding territories within the immediate range of 5 km or so of the site (e.g. Haggis: 64, 1999; Manning: 234, 1994; Whitelaw: 101, 2019). The use of multiple production zones by the Sissi people between EM II and MM II, possibly also including lower slopes further from the shore in addition to the coastal plain/s, can also be seen as a buffer against climate instability and vulnerability of coastal sites (Moody, 2012: 259–64). To some extent variation in human enamel $^{87}Sr/^{86}Sr$ values, may also reflect variation in the composition of people's childhood diet in terms of proportions of foodstuffs of higher and lower strontium concentration and of different associated $^{87}Sr/^{86}Sr$ signatures: for instance meat and milk that contain less strontium compared to plant foods will have a rather small impact on the average human skeletal strontium isotope signatures compared to that of the strontium-rich plants consumed by the respective people (Montgomery and Evans: 125, 2009; Ezzo: 7, 1994).

The observed variation in the human enamel strontium signatures of the Sissi cemetery individuals may equally be explained by small-scale, short-range residential mobility and the settling of newcomers at Sissi from contemporary sites in its immediate periphery. As mentioned above, during the late Prepalatial period, settlement nucleation and contraction take place in the Sissi region and earlier sites are abandoned except for Malia and Sissi (Whitelaw, 2012).

Owing to similarities in the underlying geology of the broader region of Sissi and the contemporary neighbouring sites along the north-east coast of the island (Nafplioti, 2011), we cannot distinguish between individuals born and raised in the former or the latter regions using strontium isotope data alone. On present human strontium data we cannot reject the possibility that, in this period, both Sissi and Malia, the cemetery of which remains insufficiently known (Legarra Herrero, 2014), operated as a regional hub and/or that their respective cemeteries may also (occasionally) have served nearby satellite settlements (Driessen, 2001, 2010; Müller-Celka, 2016). Since they are the only sites that have yielded continuous evidence for burial throughout the various periods and this despite the presence of sites of the EM II and MM II periods known in the region, part of the contributing population of the Sissi cemetery may have been external. Nor can we test for any sex-pattern in data variation and whether marital patterns may (partly) account for any intra-island residential mobility (as demonstrated in Bentley et al., 2005), owing to the small number of Sissi individuals, who could be confidently sexed.

5.2. Variation in oxygen isotope ratio values

We analysed oxygen isotope ratio signatures from all human individuals tested for $^{87}Sr/^{86}Sr$ to explore if the oxygen data can shed additional light on the geographical origins of the respective people.

The human enamel $\delta^{18}O_p$ signatures on Fig. 10 follow a rather broad data distribution (17.3‰ to 20.0‰ (mean 18.7 ± 1.2‰, 2σ). To a great extent this probably also reflects the breastfeeding effect and the enrichment of $\delta^{18}O_p$ values from the M1s analysed. If we correct for this effect by subtracting 1‰ from the M1 δ^{18}Op values, the $\delta^{18}O_p$ range narrows down to between 16.9‰ and 19.0‰ (mean 17.9 ± 1.2‰, 2σ) with corresponding corrected drinking water values between −7.9‰ and −4.9‰ (mean −6.4 ± 1.7‰, 2σ) (Tables 1 and 3, Fig. 11). Descriptive analyses were applied to the corrected $\delta^{18}O_{dw}$ signatures and these appear to be normally distributed (Shapiro-Wilk Test: p = 0.744) (Table 3). The 1.5IQR method did not detect any outliers either (Table 3).

Due to the lack of empirical data on the range of oxygen isotope ratio variation for the local Sissi population, as we have for other sites where the local $^{87}Sr/^{86}Sr$ signatures could be used to determine corresponding local $\delta^{18}O_p$ values (e.g. Hughes et al., 2014; Eckardt et al., 2009), we were not able to determine local $\delta^{18}O_p$ ranges for humans in this context. Instead we used published δ^{18}O data on modern precipitation (Lykoudis and Argiriou, 2007) to extrapolate what might be acceptable drinking water δ^{18}O values for the Bronze Age inhabitants of Sissi. These data suggest that modern $\delta^{18}O_{mw}$ values across Crete range between −5 and −7‰ with the more positive values occurring on the coastal areas and the more negative towards the interior of the island. Therefore these data are in good overall agreement with the $\delta^{18}O_{dw}$ values measured from the Sissi individuals and suggest provenance from within the island, which is also consistent with the corresponding strontium isotope data.

In addition, the Sissi human enamel $\delta^{18}O_{dw}$ data are compatible with normal variation within a population. Variation in human enamel δ^{18}O values has been shown to be linked largely to physiological factors and the use of more than one sources of water with different oxygen isotope values (Lightfoot and O'Connell, 2016). Lightfoot and O'Connell (2016) have shown that the range of δ^{18}O values within most archaeological populations can be >3‰. Such a range is higher than the range of the oxygen data from Sissi. Nevertheless, although the Sissi oxygen data are consistent with the inhabitants of a single site, we may argue, that, based on the range of the modern precipitation $\delta^{18}O_{mw}$ values from across the island (−5 and −7‰), they are also potentially consistent with provenance from anywhere in the island; not necessarily Sissi only.

Two additional points that will be worthwhile to look into are the potential chronological and/or spatial patterning of human isotopic data. Because studies on the chronology of the bioachaeological data of the site are in progress, we are not yet able to conclusively discuss these, but once these studies are completed and the relevant data are finalized we will examine them against the isotopic data from the site with a view to furthering our understanding of the observed data variation. Under an improved chronological resolution of the data, we may be able to further investigate settlement nucleation by looking into fluctuations in the variability of the strontium signatures and a probable increase during the period when other nearby EBA sites appear to have been abandoned.

Table 3
Descriptive statistics for corrected $\delta^{18}O_{dw}$ values from Sissi human enamel.

Statistic	
Mean	−6.4
Median	−6.4
Count	26
Std. Deviation	0.85
Minimum	−7.94
Maximum	−4.86
Range	3.08
Interquartile range (IQR)	1.19
Skewness (standard error)	0.07 (0.46)
Kurtosis (standard error)	−0.61 (0.89)
Shapiro-Wilk test (p value)	0.744

6. Conclusions

The human strontium and oxygen isotope signatures of the individuals buried in the cemetery are in line with provenance from within the broader region of Sissi or even the bay of Malia on the north-east coast of the island. The strontium isotope values, in particular, point to a diverse substrate geology in agreement with that reported for Sissi and its immediate surroundings within a 5 km radius, while the oxygen data match the variation of modern precipitation δ^{18}O values from the island and are consistent with a provenance from within the island. The human strontium results throughout the different phases attested in the cemetery are consistent with mobile lifeways at least for the great majority of the people studied, the use of different feeding territories in proximity to the site and possibly also variation in childhood diet. We can envisage several scenarios to explain these results. On the one hand, it may indicate that short-range mobility, which needed not exceed a radius of 5 km, was part of people's lives at Pre- and Protopalatial Sissi. They were moving as part of their daily routine to cultivate the land, herd their flocks and/or hunt or fish. It could also mean that some of the individuals had relocated from sites nearby within the Malia bay. A combination of both explanations is also possible: Maximization of the exploitation of arable land to extend the agricultural resource base largely coincides with settlement nucleation and population growth towards the late Prepalatial period, when contemporary nearby sites are abandoned, while use of multiple production zones by the people at Sissi may also be seen as a buffer against climate instability and vulnerability of coastal sites. A third explanation, however, cannot be excluded. The data could also suggest that people from surrounding hamlets within the 5 km radius around the site, rather than being buried close to their homes, were concentrated at death within the settlements that formed social arenas for the region, *in casu* Sissi and Malia (Relaki, 2012). The possibility of having a participation of larger groups in the funerary feasts that accompanied these burials throughout the different phases (Legarra Herrero, 2014), may have been the main instigation behind this final mobility. In this sense, mobile lifeways also led to mobile afterlifeways.

CRediT authorship contribution statement

Argyro Nafplioti: Conceptualization, Methodology, Formal analysis, Investigation, Funding acquisition. **Jan Driessen:** Conceptualization, Resources, Funding acquisition. **Aurore Schmitt:** Resources. **Isabelle Crevecoeur:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to the Hellenic Ministry of Culture and Sports and the Archaeological Service of East Crete for facilitating our research at Sissi in general and on diet and mobility in particular and also for their permission to sample the archaeological skeletal collection from the site for the purposes of this work. Research at Sissi is funded by the UCLouvain, INSTAP, the Belgian School at Athens, the Loeb Classical Library, the Rust Family Foundation, the FNRS, the CNRS and private sponsors. Travel expenses and the analytical costs for the oxygen isotope ratio analysis were covered through research funding from a Marie Skłodowska-Curie Individual Fellowship and a grant from the D.M. McDonald Grants and Awards Fund that were both awarded to A. Nafplioti for her project entitled EPOCH GeoChem (project number 654736), while the Katholieke Universiteit Leuven via I. Schoep sponsored the strontium analyses. Without the above financial support this research would not have been possible. We are also very thankful to the two anonymous reviewers for their constructive comments.

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