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

Argyro Nafplioti, Jan Driessen, Aurore Schmitt, Isabelle Crevecoeur

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Title Page Information

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Author names and affiliation:

Argyro Nafplioti^a (corresponding author), Jan Driessen^b, Aurore Schmitt^c, Isabelle Crevecœur^d

^aMcDonald Institute for Archaeological Research, Downing Street, Cambridge CB2 3ER, e-mail: argyro.nafplioti@googlemail.com

^bUCLouvain, Aegis/CEMA/INCAL, Belgium, e-mail: jan.driessen@uclouvain.be

^cAix Marseille Univ, CNRS, EFS, ADES, Marseille, France, e-mail: Aurore.SCHMITT@univ-amu.fr

^dUMR 5199 PACEA, CNRS, Universite de Bordeaux, Pessac, France, e-mail: sabelle.crevecœur@u-bordeaux.fr

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 surroundings, as well as with strontium isotope results from snail samples also collected from the broader Sissi region. In a fashion similar to the strontium data, the human oxygen isotope data point to access to different feeding territories in close proximity to the site and possibly also to variation in the composition of childhood diet, while some short-range immigration cannot be excluded either.

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. Moreover, 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.

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 marital network systems some of them had moved in from nearby sites, or both the above.

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

Highlights

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

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

analyses to offer a more nuanced understanding of past populations, their diets, potential origins and aspects of their mobility (Figure 1) (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 (Figure 2). On present evidence, the site was occupied from Early Minoan IIA (c. 2600 BCE) onwards when a village was constructed on the southeast side of the promontory. It formed, together with Malia, part of a series of villages that existed along the coast of the Malia bay that extended from Stalidha to the west to Milatos to the east. From then onwards, the site of Sissi remained occupied till the advanced Late Minoan IIIB period (c. 1230 BCE), as did Malia. This longevity of occupation can undoubtedly be explained by its advantageous strategic location. Situated 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. From EM IIA onwards, the north side of the hill 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 especially during the Middle Bronze Age (e.g. Schoep et al., 2012: 32-35). The bioarchaeological and chronological analyses are still ongoing. However, 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 (Figure 3). On the lowest terrace in the east part (Zone 1), one collective burial¹ and one ossuary² (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 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, 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 (1.18) 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 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 plan in figure 3 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.

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.

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 (Hoppe et al., 2003; Hillson, 2002; Price et al., 2002, White et al., 1998).

2.2.1 Strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ values (c. 0.715) than recent volcanic rocks (c. 0.704) (Wright 2005). Strontium isotope ratios in marine sedimentary rocks depend on the $^{87}\text{Sr}/^{86}\text{Sr}$ 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, $^{87}\text{Sr}/^{86}\text{Sr}$ largely reflects local geology, and passes from the bedrock into the soil, the groundwater and the food chain. Thereby $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ in sea spray (Veizer, 1989), atmospheric deposition (Miller et al., 1993) and in modern contexts fertilizers too, can also impact on local $^{87}\text{Sr}/^{86}\text{Sr}$ signatures, the latter largely reflect bedrock geology and mineral weathering (Bentley, 2006.). Thus $^{87}\text{Sr}/^{86}\text{Sr}$ 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, 2002:148; Ubelaker, 1989), $^{87}\text{Sr}/^{86}\text{Sr}$ 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. Thus cortical bone $^{87}\text{Sr}/^{86}\text{Sr}$ signatures more closely reflect the dietary intake of the last 10 years of life, and 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 site of residence prior to death (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 $^{87}\text{Sr}/^{86}\text{Sr}$. They provide an average of the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ values measured from his/her tooth enamel should be 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 be in overall agreement to comparable data from local geological material(s). Otherwise, if tooth enamel $^{87}\text{Sr}/^{86}\text{Sr}$ signatures are found to be significantly different from the local $^{87}\text{Sr}/^{86}\text{Sr}$, 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 ($^{18}\text{O}/^{16}\text{O}$) analysis

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

Moreover, owing to much overlap in human $^{18}\text{O}/^{16}\text{O}$ 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 (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. Less than 1km 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 Permian-Triassic shales, phyllites, quartzphyllites and quartzites. Upper Miocene to Lower Pliocene limestones extend immediately to the east of the site, while no more than 5km 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 twenty-six 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 $^{87}\text{Sr}/^{86}\text{Sr}$ signatures in bone samples. The latter, including isotope ratio values from four 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 $^{87}\text{Sr}/^{86}\text{Sr}$, 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 $^{18}\text{O}/^{16}\text{O}$ analysis, we aimed for the second permanent molar (M2), because the M2 enamel is known to form largely between the age of seven and eight (Scheuer and Black, 2000; Ubelaker, 1989) and therefore the measured $^{18}\text{O}/^{16}\text{O}$ signatures are not expected to be affected by the consumption of mother's milk (Jay et al. 2008; Hoppe et al., 2003; Hillson, 2002; Montgomery, 2002; White et al., 2000; Wright and Schwarcz, 1998). 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. Where the M2, however, could not be sampled, it was substituted by the first molar (M1), an earlier forming tooth, 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 $^{87}\text{Sr}/^{86}\text{Sr}$ analysis, including procedures of sample extraction and sample preparation prior to analysis, have been described in earlier publications (Nafplioti 2008, 2009, 2011). Preparation and analysis of the samples were carried out at the National Oceanography Centre in Southampton, where the actual $^{87}\text{Sr}/^{86}\text{Sr}$ values were measured to the sixth decimal digit by a ThermoFisher TRITON Plus Thermal Ionization Mass Spectrometer (7 Collectors).

3.2.2. Oxygen isotope ratio analysis

$^{18}\text{O}/^{16}\text{O}$ 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 $^{13}\text{C}/^{12}\text{C}$ 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 $^{18}\text{O}/^{16}\text{O}$ carbonate values can easily be converted to the corresponding $^{18}\text{O}/^{16}\text{O}$ phosphate values (see Bryant et al., 1996; Iacumin et al., 1996a).

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 and colleagues (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 (0.1ml/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 hour, and then at -80°C for an additional 30 minutes before being freeze dried for 90 minutes. 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 CO_2 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. $\delta^{18}\text{O} = 1000 \times [(^{18}\text{O}/^{16}\text{O} \text{ sample})/(^{18}\text{O}/^{16}\text{OVPDB}) - 1]$, (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 $\pm 0.08\text{‰}$ for $^{13}\text{C}/^{12}\text{C}$ and better than $\pm 0.10\text{‰}$ for $^{18}\text{O}/^{16}\text{O}$.

4. Results

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

The human tooth enamel strontium isotope ratios range between 0.70860 and 0.70971 (mean: 0.70939, 0.00048 2σ) (Table 1, Figures 4, 7 and 8). 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 ($\sigma=0.00002$), the Ailias ($\sigma=0.00010$), Gypsades ($\sigma=0.00003$), and Sellopoulo ($\sigma=0.00015$) collections from Knossos, but lower compared with Manika on Euboea ($\sigma=0.00065$), the Chora of Naxos ($\sigma=0.00044$) and Knossos South of the Palace ($\sigma=0.00025$) (Nafplioti 2007, 2008, 2009a, 2009b, 2012b).

Strontium isotope signatures from snails collected from the excavation site (1) and the neighbouring village of Vrahasi (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 $\delta^{18}\text{O}_\text{c}$ values which are reported relative to the VPDB international standard. In order to facilitate comparison of the human $\delta^{18}\text{O}_\text{c}$ 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 the equation below (1)

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

and calculated the corresponding $\delta^{18}\text{O}$ values for drinking water ($\delta^{18}\text{O}_\text{dw}$). Converting the human phosphate $\delta^{18}\text{O}$ to $\delta^{18}\text{O}$ 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; Pollard et al., 2011; Chenery et al., 2010; 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 and colleagues (1996) to reflect the correlation between $\delta^{18}\text{O}$ values measured in the structural carbonate and phosphate components of apatite, respectively, as follows (2, 3):

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

and

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

373 Then

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

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 $18.7 \pm 1.2\text{‰}$, 2σ)
 378 with corresponding drinking water values between -7.3 ‰ and -3.4‰ (mean $-5.3 \pm 1.7\text{‰}$, 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,

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

Figure 7 plots the human tooth enamel and bone $^{87}\text{Sr}/^{86}\text{Sr}$ signatures together with data on the local biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ measured from snail shells from the site and the broader region. The human cortical bone values reflect adult diet during the last 10-15 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 5km, as described in Section (2.3) above. Intra-group variation ($\sigma=0.00088$) 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 (Figures 4 and 8).

If we look carefully at the Sissi human enamel $^{87}\text{Sr}/^{86}\text{Sr}$ data, these generally fit provenance in coastal areas where marine strontium from seaspray, rainwater and shell sands have a significant impact on the local biosphere Sr values, i.e. around 0.7090-0.7092 (Montgomery et al., 2007; Bentley, 2006: 153; Montgomery et al., 2003; Veizer, 1989). Nonetheless, the $^{87}\text{Sr}/^{86}\text{Sr}$ value from individual SAN7, who was statistically identified as an outlier, falls below the modern seawater $^{87}\text{Sr}/^{86}\text{Sr}$ constant of 0.7092 (Veizer 1989). Albeit not compatible with an origin from a coastal site, the $^{87}\text{Sr}/^{86}\text{Sr}$ value from SAN7 does not exclude an origin within the island. Strontium isotope ratios similar to SAN7 from Burial Building 9.1, although rare amongst the local bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ signatures from Crete, are not altogether absent. In fact, the two lowest $^{87}\text{Sr}/^{86}\text{Sr}$ 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.

The remainder of the Sissi human enamel $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (0.70915 to 0.70946) and can thus be identified as locals at Sissi. Moreover, based on the $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ signatures probably reflect older geological formations and different catchment areas for the respective individuals compared to burials with lower $^{87}\text{Sr}/^{86}\text{Sr}$ signatures that are close to the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ constant. The human enamel $^{87}\text{Sr}/^{86}\text{Sr}$ results therefore point to extensification of land use in this period and access to different feeding territories in close proximity to the site (e.g. Haggis, 1999: 64; Manning, 1994: 234), for instance within a radius of a couple of kilometers. The use of multiple production zones by the Sissi people 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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, 2009: 125). Alternatively, some of the Sissi individuals may have been born and raised in nearby sites, so that the observed high human enamel $^{87}\text{Sr}/^{86}\text{Sr}$ variation may also reflect small-scale, short-range intra-island residential mobility. This probability, however, cannot be adequately assessed using strontium data alone due to overlapping bioavailable strontium isotope signatures across parts of the island linked to similarities in the underlying geology (Nafplioti, 2011, 2015). 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

The human enamel $\delta^{18}\text{O}_p$ signatures on Figure 4 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 $\delta^{18}\text{O}_p$ values from the M1s analysed. If we correct 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 between 16.9‰ and 19.0 ‰ (mean 17.8 ± 1 ‰, 2σ) with corresponding drinking water values between -7.9‰ and -4.9‰ (mean -6.4 ± 1.7 ‰, 2σ) (Table 1, Figure 8).

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 $^{87}\text{Sr}/^{86}\text{Sr}$ signatures could be used to determine corresponding local $\delta^{18}\text{O}_p$ values (e.g. Hughes et al 2014; Eckardt et al., 2009), we were not able to determine local $\delta^{18}\text{O}_p$ ranges for humans in this context. Instead we used published $\delta^{18}\text{O}$ data on modern precipitation (Lykoudis and Argyriou, 2007) to extrapolate what might be acceptable drinking water $\delta^{18}\text{O}$ values for the Bronze Age inhabitants of Sissi. These data suggest that modern $\delta^{18}\text{O}_{\text{mw}}$ 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. These data thus are in good overall agreement with the $\delta^{18}\text{O}_{\text{dw}}$ values measured from the Sissi individuals and with provenance within the island that had also been suggested based on the corresponding strontium isotope data.

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

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 bioarchaeological data of the site are in progress we are not yet able to conclusively discuss these, 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.

6. Conclusions

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

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, 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.

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

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Figure 2

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Figure 3

Figure 4

Figure 5

Figure 7

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