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MOVING FORWARD: STRONTIUM ISOTOPE MOBILITY RESEARCH IN THE AEGEAN

Argyro Nafplioti

Institute of Molecular Biology & Biotechnology, Foundation for Research & Technology, Hellas (FORTH)
(argyro.nafplioti@googlemail.com)

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ABSTRACT

Provenance, residential mobility and migration are recurrent themes in archaeological research. Since the 1980s, initially in America and Northern Europe, strontium isotope analysis of archaeological skeletal remains has revolutionized research on provenance and mobility. Nevertheless, such research normally identifies migration and mobility simply as events, rather than processes that need to be further characterized into their particulars. In Aegean Archaeology, more than ten years following the first ever announcement of strontium isotope results from Greece at the 10th Cretological Congress in 2006 and the first papers using this methodology, new to this context research teams have started to contribute into an ongoing scholarship in the field. Given the growing interest in this type of research, it is high time that we critically reviewed the data in hand. To this end, this paper discusses the more than 450 samples the author has analysed for strontium isotope ratio from the Aegean and reviews the potential and limitations of strontium research in this context. Drawing examples from published work, common pitfalls are flagged up with the intention to help strontium research to move forward. Further, in order to more effectively and systematically characterise past mobility and migration with a view to better understanding its motivations and consequences, we propose to combine a methodologically sound research with a theoretically informed social bioarchaeology of migration. We argue that the way forward for research of this kind is to move beyond a mere fingerprinting of migration/relocation episodes, towards an investigation of these themes in the ancient world through a different paradigm, wherein the individual is central and migration and mobility are studied themselves as multi-layered processes.

KEYWORDS: Strontium isotope ratio, $^{87}Sr/^{86}Sr$, provenance, residential mobility, migration, social bioarchaeology, Aegean

1. INTRODUCTION

Migration and residential mobility are amongst the most popular topics of archaeological research with fluctuating influence on archaeological thinking depending on the theoretical models predominant at the given time (Anthony, 1997; Trigger, 2008). Cultural historical approaches for instance that equate certain material culture characteristics, archaeologically inferred practices and ideologies with certain people, largely consider any inter-regional stylistic and ideological similarities and imports to be results of population influx (Kossina, 1911, Montelius, 1903). More recent research, however, has shown that viewing population residential mobility as the exclusive determinant of culture history, can be highly problematic (Binford, 1965; Bintliff, 1994; Lyons and Papadopoulos, 2002:5; Renfrew, 1972; Tournavitou, 1990; Wilson, 1987). It is equally possible that culture change and inter-regional culture similarities may reflect inter-regional contacts and the transfer of goods, ideas or technologies with no significant population influx. In relation to this, with the aid of advances in biogeochemical research, since the 1980s there is a growing interest in using isotopic analysis of human skeletal remains to investigate provenance and mobility, often with a view to improving understanding of connectivity and interaction, cultural change and discontinuity in the past (Burmeister 2000; Cabana and Clark, 2011; Chapman and Hamerow, 1987; Cherry and Leppard, 2014; Crellin, 2020; Cusick, 2015; Renfrew, 1971; Rouse, 1986; Triger, 2008; van Dommelen, 2014). Initially in America and Northern Europe and later also in the rest of the globe, analysis of isotope ratios of certain elements, such as strontium, oxygen and sulphur (Evans et al., 2019; Chenery et al., 2010; Killgrove and Montgomery 2016; Knipper et al. 2017; Knudson and Price, 2007; Madgwick et al., 2019; Mitchell and Millard, 2009; Nafplioti et al., 2021), which are known to vary with the local geological and environmental conditions, have been employed to track provenance and trace residential mobility. In addition, natural variation in the distribution of stable isotopes of carbon and nitrogen throughout different ecosystems enables their use as natural dietary tracers. As different dietary practices may also reflect different populations (Sarpaki, 2009), carbon and nitrogen isotopes in addition to isotopes of strontium, oxygen and suphur have also been used as proxies to identify different, new populations, and thus track and interpret past residential mobility (e.g. Bentley, 2013; Chenery et al., 2009; Diaz et al., 2012; Nehlich et al., 2009). Of these methods, analysis of strontium isotopes is the most popular one in research of this kind, and is reviewed in this paper with reference to its potential, limitations and future applications, with a particular focus on the Aegean region.

In essence, isotope ratio analysis of archaeological skeletal remains measures a chemical 'fingerprint' within human or animal bones or teeth, which can be directly linked to food and water ingested by the individual. This is based on the principle that largely 'you are what you eat', which describes the processes by which molecules consumed as food or water are incorporated into consumers' body tissues, and therefore a chemical signal that is passed either unchanged or altered in a quantifiable fashion, from dietary intake into the body, can be linked back to the intake. Isotope ratios of strontium in particular, which this paper will examine, largely relate to local bedrock geology, and can thus provide information on an individual's geographical origin and track residential mobility between geologically and isotopically different regions/sites (Bentley, 2006; Liritzis et al. 2020; Price et al., 2002).

In addition, more recent advances in isotope analysis in terms of research methodology and theoretical background have further improved our ability to identify both short- and long-term residential mobility through sequential and micro-sampling, and have enabled us to move beyond the simple dichotomous classification of past individuals as either local or non-local (Balasse et al., 2002; Scharlotta and Weber, 2014); to shed light on the nuances of migration and its implications for the social groups involved, i.e. the people moving, the receiving communities as well as those staying behind (Bentley et al., 2012; Gregoricka, 2021; Valentine et al., 2015; Zakrzewski, 2011); and to advance to a more informed understanding of the complexity of these processes, the motivations and consequences for all parties involved. In other words, these advances have helped us look more closely into the 'how' and 'why' of mobility at a given time in the past, as well as the socio-economic and biological implications of these relocations. In this way, migration or mobility is not simply identified as an event, but it is rather defined as a socio-cultural phenomenon (Burmeister, 2000; Frieman et al., 2019; Uteng and Cresswell, 2008; van Dommelen, 2014): who is moving, where from, why, under what circumstances and with what consequences? Insights into past lifeways and social organization, and a more holistic approach to the problem are made possible. While at the same time, all new knowledge on relocations in the past generated though archaeological research can be applied to better understand contemporary large- and small-scale human movements (Nafplioti, in preparation; Tsuda et al., 2015).

In this broader context, this paper will examine the current state of the art for strontium isotope ratio mobility research in the Aegean. More than ten years following the first ever announcement of strontium isotope ratio results from Greece at the World Archaeology Inter-Congress in Osaka and the 10th Cretological Congress at Chania in 2006, and the first publications in Aegean Archaeology using this methodology (Nafplioti, 2006, 2007, 2008; Richards et al., 2008), there is a growing number of new to this context research teams (Issakidou et al., 2019; Panagiotopoulou et al., 2018; Triantaphyllou et al., 2015; Vaiglova et al., 2018; Wang et al., 2019; Whelton et al., 2018) and of associated scholarship that covers the period from the Palaeolithic to the Early Iron Age times. In response to this surge of studies on strontium isotope mobility in Greece, a critical review of the data in hand is ever so timely. To this end this paper discusses the potential and limitations of strontium isotope ratio research in this context and asks the following pertinent questions: 'Where do we stand?' and 'How do we move forward?' Taking also into consideration shortcomings in some of the more recent relevant published work, this paper identifies potential pitfalls and gives recommendations for most effective practices for research planning and sampling, for data analysis as well as for framing archaeological interpretation of past residential mobility and migrations.

2. PRINCIPLES OF $^{87}Sr/^{86}Sr$ ANALYSIS

Strontium isotope ratio ($^{87}Sr/^{86}Sr$) analysis of skeletal remains is the most popular isotopic application in research on past population residential mobility and provenance. It uses $^{87}Sr/^{86}Sr$ signatures as a proxy for local geology in order to determine the geographical origins of the individuals examined and distinguish between locals and non-locals at the sites investigated. The principles of $^{87}Sr/^{86}Sr$ analysis are well documented (Bentley, 2006; Evans et al., 2009; Price et al., 2002), and they have also been discussed in detail in earlier relevant work of the author (Nafplioti 2008, 2011, 2012a).

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 on the age of the rocks (Rogers and Hawkesworth, 1989). As rubidium is much more abundant in crustal materials than in the Earth's mantle, old metamorphic rocks of crustal origin have more radiogenic (higher) $^{87}Sr/^{86}Sr$ values (c. 0.715) compared to recent volcanic rocks (c. 0.704) (Wright 2005). In marine sedimentary rocks strontium isotope ratios depend on the $^{87}Sr/^{86}Sr$ value of seawater at the time the rocks were formed and largely vary between 0.707 and 0.710 (Elderfield, 1986; Palmer and Elderfield, 1985).

$^{87}Sr/^{86}Sr$ 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 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 (Bentley, 2006: 142; Graustein 1989; Thomsen and Andreasen, 2019), can also impact 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 feeding territories of the people analysed.

Different skeletal tissues represent different periods in people's life. For instance, 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). As such, tooth enamel $^{87}Sr/^{86}Sr$ signatures reflect early childhood diet and the respective local feeding territory where an individual spent those years; hence their provenance. In addition, due to the different timing of tooth formation, different teeth represent different times in a child's life and different developmental stages (Beaumont et al., 2013; Eerkens et al., 2011; Hillson, 2002; Ubelaker, 1989). For instance, the permanent M1 and M2 tooth enamel largely represents years 3-5 and 6-10 in one's life, respectively. Conversely, bone and, to a lesser extent, also dentine undergoes continuous replacement of their mineral phase in the course of life. Thus, cortical bone $^{87}Sr/^{86}Sr$ signatures more closely reflect the dietary intake of the last 10-20 years and human bone $^{87}Sr/^{86}Sr$ values can be used to characterize the local bioavailable $^{87}Sr/^{86}Sr$ at one's latest residence (Ezzo et al., 1997; Ezzo and Price, 2002; Grupe et al., 1997; Hedges et al. 2007; Hillson 2002; Sealy et al., 1995; Manolagas 2000; Nafplioti, 2008; Price et al., 1994; Tafuri et al., 2006). In essence therefore strontium isotope analyses of tooth enamel and bone can help reconstruct dietary life-records over different periods of people's or other animals' life and potentially trace relocation between geologically different contexts.

In addition, tooth enamel is denser, harder and more inert than bone or dentine, and therefore more resistant to post-burial isotopic contamination than the latter (Budd et al., 2000; Chiaradia et al., 2003; Hoppe et al., 2003; Kohn et al., 1999; Lee-Thorpe and

Sponheimer, 2003; Price et al., 1985). Under diagenetic conditions, bone and dentine isotope signatures can potentially fully calibrate to those of the burial environment, often resulting in a quite homogeneous range of signatures. Even so, they can still serve as a proxy for local geology as they will reflect the geology of the burial site. In addition, cremated bone in particular has been shown to preserve the biogenic $^{87}Sr/^{86}Sr$ signatures and be minimally affected by diagenetic processes. Thereby it is at least as reliable as tooth enamel in analyses of this kind (Snoeck et al., 2016). Acknowledging, however, the possibility of recent immigrants amongst the individuals tested, whose bone values had not fully calibrated to their latest residence by the time they died, samples from archaeological and/or modern animal skeletal tissue 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. Bentley et al., 2004; Nafplioti, 2012a; Price et al., 2002; Wright, 2005), which the humans occupying the same sites also had access to. Also, as regards the archaeological animals in particular, the human individuals from the same sites/regions most probably fed on these animals and/or their products. 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 consistent with the local bedrock geology and 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.

In order to characterise the local bioavailable $^{87}Sr/^{86}Sr$ and distinguish between locals and non-locals at the site/s under investigation, studies of this kind alternatively also use modern plants, soil and/or water samples (Evans et al., 2009; Evans et al., 2010; Isaakidou et al., 2019; Panagiotopoulou et al., 2018; Vaiglova et al., 2018). Nevertheless, plants and soil strontium isotope signatures can be too 'local' as in the case of diagenetic bone above. In modern contexts, plants, soil and water samples can also be susceptible to contamination by fertilizers (Bentley, 2006: 142; Frei and Frei, 2011; Graustein 1989) and/or atmospheric pollution (Miller et al., 1993). Thomsen and Andreasen (2019) showed that the use of agricultural lime can impact biosphere strontium signatures measured from water and plant samples from farmlands and mislead data interpretation in strontium isotope studies of mobility. Also, phosphate fertilisers have strontium concentrations, which range between 20 mg/kg and 4000 mg/kg (ATSDR, 2004), and can thus potentially significantly impact biosphere strontium signatures. Moreover, if the range of $^{87}Sr/^{86}Sr$ values from the plant, water and/or soil samples from the region/site under investigation is broad, the possibility of getting false positive identifications (for local origins) is higher than it would be if animal samples were used, as the latter average the $^{87}Sr/^{86}Sr$ from their feeding territories. Plant and soil samples can give 'too local' $^{87}Sr/^{86}Sr$ signatures, as we argued above, while $^{87}Sr/^{86}Sr$ signatures from local rivers/streams can preferentially reflect certain local rocks/minerals over others and their corresponding $^{87}Sr/^{86}Sr$ signatures (Bentley, 2006: 143-8). Analysing different types of soil, plants and water from more than one source can give a broad range of $^{87}Sr/^{86}Sr$ values. Provided there is no mobility, this range should be, at the very least, wider in comparison to that from human/animals from the same site/region. That is because archaeological or modern animals average the bioavailable $^{87}Sr/^{86}Sr$ in their catchment area through the food and water they consume and thereby reduce the width of the associated range of $^{87}Sr/^{86}Sr$ values (Burton et al. 1999).

Because animal tissues provide an average of the bioavailable $^{87}Sr/^{86}Sr$ signatures of the feeding territories that these animals occupied in life, it can be argued that samples from archaeological or small modern animals skeletal tissues, such as snails or rodents, can offer an accurate measure of the range of local $^{87}Sr/^{86}Sr$ values in soils, plants and waters in the areas under investigation, which is also a more conservative estimate of the local bioavailable $^{87}Sr/^{86}Sr$ at a given site/region compared to soil, plants and/or water values, due to the averaging effect of skeletal tissue formation on $^{87}Sr/^{86}Sr$ ranges (Bentley et al., 2004; Burton et al. 1999; Nafplioti, 2012a; Price et al., 2002; Wright, 2005). Archaeological animals are preferred to modern ones due to potential contamination of modern contexts by fertilizers and/or atmospheric pollution, discussed above. Also, tooth enamel in particular is preferable since it is more resistant to chemical and physical post-depositional modifications compared to bone and dentine (Bentley, 2006; Kohn et al., 1999).

3. MATERIALS AND METHODS

The author analysed the majority of the over than 450 samples of human and animal skeletal tissue, which are discussed below in relation to the potential and limitations of $^{87}Sr/^{86}Sr$ research in the Aegean, at the National Oceanography Centre Southampton (NOCS), while a smaller part of these samples were analysed at the Department of Earth Science of the University of Cambridge. The analytical protocol for $^{87}Sr/^{86}Sr$ analysis, including procedures of sample extraction and sample preparation prior to analysis, as well as the actual measurement of the $^{87}Sr/^{86}Sr$ values have been have been detailed in earlier publications (Nafplioti, 2008, 2009, 2011).

Samples of tooth enamel, bone and shell (> 20mg) were placed in the ultrasonic bath for a total of 30 minutes to remover surface contamination. The bath was interrupted every 10 minutes and the specimens were mechanically cleaned using ultrapure water (18.2Ω). 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 2ml 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 3ml H_2O and 3ml of SB 3M HNO_3. The matrix and everything except Sr and Rb was eluted with 2.5 ml of SB 3M 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 VG-Micromass Sector 54 thermal ionization mass spectrometer (TIMS) and a ThermoFisher TRITON Plus Thermal Ionization Mass Spectrometer (7 Collectors), both available at Southampton and Cambridge.

4. POTENTIAL AND LIMITATIONS OF STRONTIUM ISOTOPE RATIO RESEARCH IN THE AEGEAN

In order to successfully track residential mobility using strontium isotope ratio analysis, there has to be adequate variation in the bioavailable strontium signatures between the specific sites or regions under investigation and the alleged provenance of the newcomers. If variation of strontium isotope ratios is too low, analysis of strontium isotopes cannot be of much help in detecting residential mobility between sites or regions in the particular context. To mitigate low strontium isotope ratio variation other isotope systems, preferably applied in combination, should be sought. Therefore, a first step in any strontium isotope ratio investigation ideally is the assessment of spatial variation of biosphere strontium signatures in the specific study context, which can be facilitated by regional biosphere strontium maps such as those generated for instance by the pioneering works of Bentley and Knipper (2005) for southern Germany, Evans et al. (2009) for the Isle of Skye (Scotland), and Evans et al. (2010) for Britain.

Early on in strontium isotope research in Aegean Archaeology, the author identified this need as the then single biggest obstacle to the further development of this research field in Greece. To this end, for the reasons discussed in section 2 above, the author analysed archaeological and modern animal skeletal tissue and published the first map of bioavailable strontium isotope signatures in this context (Nafplioti, 2011). This map presented the first comprehensive evidence for the potential of strontium isotope ratio research to track mobility in the Aegean, while at the same time it also highlighted related limitations for specific geographical contexts. The author has since extended this dataset through other relevant published and ongoing work, including other isotope systems, which she combined with strontium (Nafplioti, 2021, Nafplioti, in preparation). These additional bioavailable strontium isotope signatures that the author published more recently (Nafplioti et al., 2021), along with similar data generated by other research teams for sites not included in the first map (Nafplioti, 2011), are in overall agreement with the latter and the author's first conclusions about the potential and limitations of strontium isotope research in the Aegean, which she presented in that publication. Here the author will summarise these results and describe how the latest relevant data confirm her first conclusions.

To date the author has analysed for $^{87}Sr/^{86}Sr$ more than 450 human and animal samples from 31 sites in Greece, mainly the central (e.g Manika, Tharrounia, Kitsos Cave) and south Greek Mainland (e.g. Mycenae, Tiryns, Franchthi), and the Aegean islands (e.g Kephala, Maroulas, Chora of Naxos, Agio Galas, Knossos, Chania). The archaeological animals sampled, represent the main domesticates, i.e. sheep, goat, cow and pig. The graph in Fig. 1 plots all $^{87}Sr/^{86}Sr$ signatures that the author has measured so far. Each bar on the graph represents a single $^{87}Sr/^{86}Sr$ signature. Black bars represent human tooth enamel strontium data, while the green ones show bioavailable strontium signatures characterised mainly from archaeological animal tooth enamel and modern snail shell samples. Archaeological animals come from the same contexts as the humans and are used in research of this kind to characterise the local bioavailable $^{87}Sr/^{86}Sr$ in the sites/regions under investigation and distinguish between local and non-local individuals.

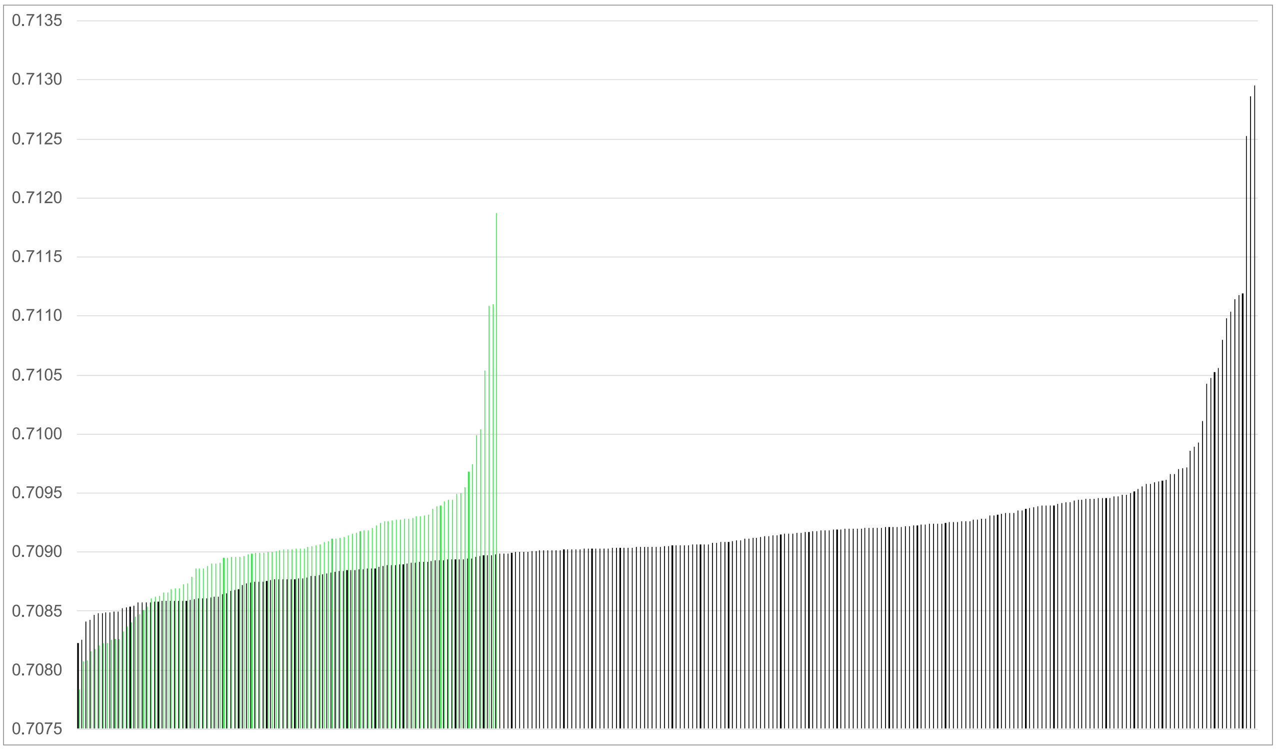

Figure 1. Strontium isotope ratio ($^{87}Sr/^{86}Sr$) values from human and animal samples from the Aegean. Key: BARS: black= archaeological human tooth enamel, green=archaeological and modern animal enamel, bone and/or shell.

Patterning of the human $^{87}Sr/^{86}Sr$ signatures on the graph shows that there is considerable variation in the human strontium data. The human enamel values range between 0.7082 and 0.7130, while the majority of the values (89%) fall between 0.7085 and 0.7095. In a similar fashion both in terms of the range of the variation and the actual isotope signatures measured, the bioavailable strontium data range from 0.7078 to 0.7119.

In addition, mapping of the variation of bioavailable signatures in the Aegean showed that strontium data variation in this region follows a clear geographical patterning and largely reflects variation in the underlying bedrock geology (Fig. 2). This suggests a marked difference between certain regions, for instance between the central Argolid in the Pindos zone, the eastern Argolid and eastern Corinthia in the Parnassos zone, and the islands of Kos and Rhodes in the south-eastern Aegean in the Sub-Pelagonian zone, where mean $^{87}Sr/^{86}Sr$ values range between 0.7082 and 0.7087, on the one hand, and the central Cyclades in the Attic-Cycladic metamorphic belt and the island of Chios (north-eastern Aegean) in the Vardar zone, which exhibit values ranging between 0.7093 to 0.7115, on the other hand. Ratios from central Euboea, south-eastern Attica, the western Cyclades and central Crete largely range between 0.7089 and 0.7091 and fall within the two ends of the range of variation of the local biologically available $^{87}Sr/^{86}Sr$ in the Aegean described above (Nafplioti 2011: 1569). In Crete, there have also been recorded a few values that are lower than 0.7089 and some higher than 0.7091, but these are rare and can be linked to the corresponding highly variegated underlying substrate geology of the region (Nafplioti et al., 2021).

The more recently published bioavailable strontium isotope ratio signatures for specific sites, such as Knossos on Crete (Isaakidou et al., 2019: 39), and/or certain lithologies of isopic/tectonic zones in the Aegean (Higgins and Higgins, 1996), such as the sub-Pegalgonian (Panagiotopoulou et al., 2018; Wang et al., 2019), Pelagonian (Panagiotopoulou et al., 2018; Whelton et al., 2018) and Vardar zones (Vaiglova et al., 2018, Whelton et al., 2018), are in overall agreement with relevant data from the same sites or isopic zones, which were reported for the first time in Nafplioti's map (Nafplioti, 2011). On the map in Fig. 2, which is a modified version of Fig. 3 in Nafplioti (2011), all bioavailable strontium isotope data published by other teams, new to this context, are marked in blue colour. Despite the fact that some of these bioavailable strontium ratios were measured from materials other than archaeological animal enamel or modern snail shells that were used in Nafplioti (2011), such as plants and water samples, variation in the data largely reflects variation in the underlying bedrock geology and the specific isopic zones into which the complex geology of the Aegean region is divided. Isopic or tectonic zones are zones that comprise groups of rocks sharing a common geological history

(Higgins and Higgins, 1996: 17). As can be seen on the map in Fig. 2, the more recent bioavailable strontium data from parts of the Greek Mainland that had not been sampled before are in overall agreement with the general pattern of strontium isotope ratios' variation in the Aegean described above. Thereby more recent data on the biovaialble strontium isotope ratio variation in this context confirm first conclusions presented in Nafplioti's map (Nafplioti, 2011) and the ever so important role of geology in the regional variation of bioavailable strontium isotope ratios in the Aegean.

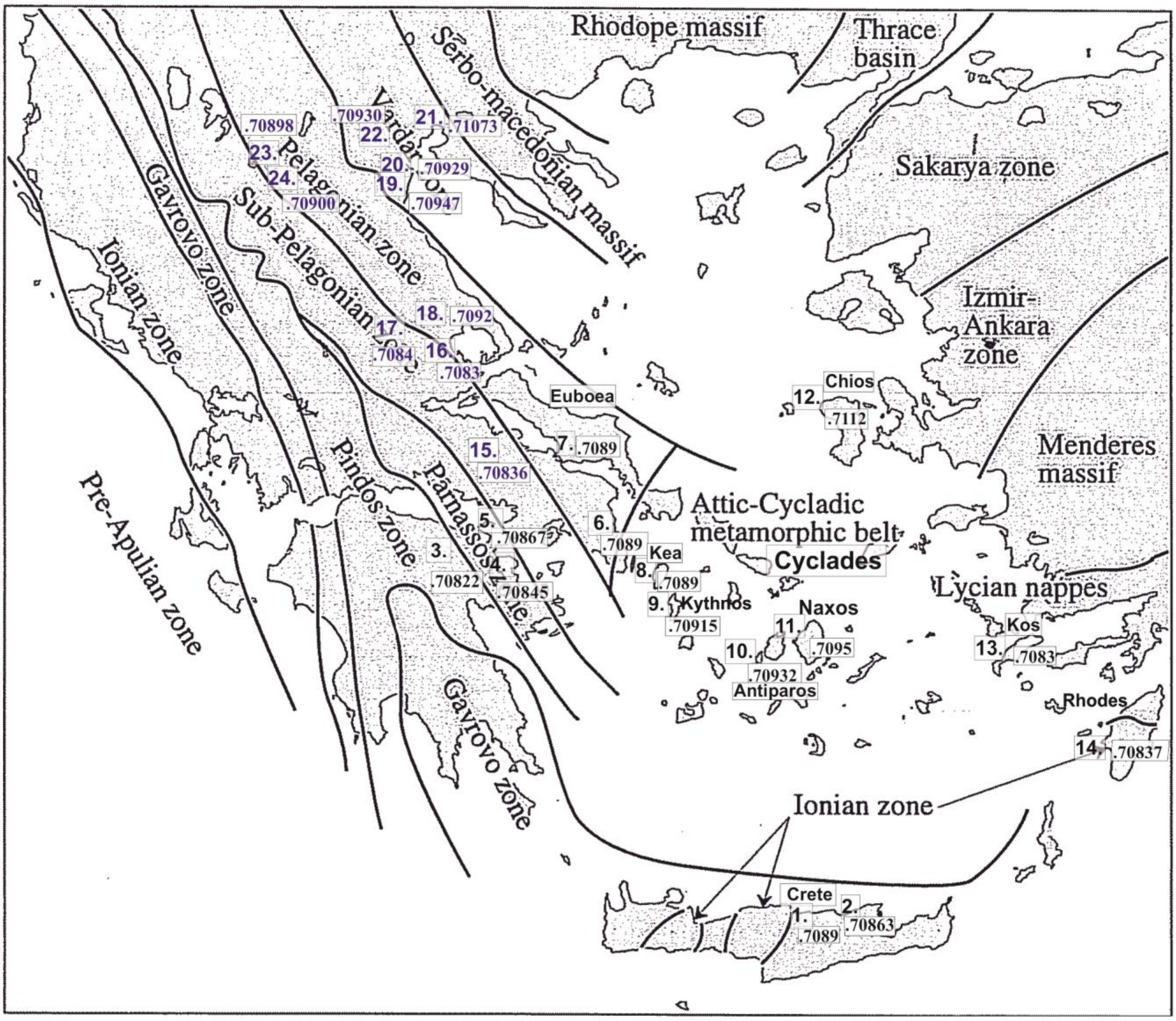

Figure 2 The map shows in black colour $^{87}Sr/^{86}Sr$ mean values from animal enamel and bone, and snail shell samples from the Aegean grouped by the geographical region and the isopic zone represented, after Nafplioti (2011: Figure 3) and Nafplioti et al. (2021). In blue colour are shown additional $^{87}Sr/^{86}Sr$ mean data from other teams (Panagiotopoulou et al., 2018; Vaiglova et al., 2018; Wang et al., 2019; Whelton et al., 2018).

Key: 1= Central Crete (n = 13), 2= North-eastern Crete (n=5), 3= Central Argolid (n = 12), 4= Eastern Argolid (n = 3), 5= Eastern Corinthia (n = 3), 6= South-eastern Attica (n = 3), 7= Central Euboea (n = 7), 8= Kea (n = 5), 9= Kythnos (n = 5), 10= Antiparos (n = 1), 11= Naxos (n = 4), 12= Chios (n = 3), 13= Kos (n = 3), 14= Rhodes (n = 1), 15= Sarakenos Cave (n=5), 16= Voulokaliva (n=6), 17= Pharsala (n=8), 18= Chloe (n=5), 19= Revenia (n=6), 20= Makriyalos (n=20), 21= Stavroupoli, 22= Paliambela (n=4), 23= Kleitos, 24= Toumba Kremastis Koiladas (for Kleitos, Stavroupoli and Toumba Kremastis Koiladas n = 14).

5. COMMON PITFALLS IN CURRENT RESEARCH AND HOW TO MOVE FORWARD

In contrast to the rest of the Mediterranean where we lack any bioavailable strontium ratio maps, Nafplioti (2011) mapped regional variation of the biovailable strontium isotope ratio signatures in the Aegean using archaeological and modern animal skeletal tissue from this context (Fig. 2). This map (Nafplioti, 2011) and later contributions of bioavailable strontium data from sites and regions mainly from northern Greece (e.g. Nafplioti et al., 2021, Panagiotopoulou et al., 2018; Vaiglova et al., 2018; Whelton et al., 2018), which had not been included in Nafplioti (2011), have set the scene for further advances in the field. More than ten years after the first ever publications of strontium isotope research on mobility and migration in the Aegean (Nafplioti 2007, 2008; Richards et al., 2008), research continues to expand uninterruptedly (Nafplioti 2009a, 2009b, 2011, 2010, 2012a, 2012b, 2015, 2018; Nafplioti et al., 2021) while latest contributions also include teams, which are new to this context (e.g. Isaakidou et al., 2019; Panagiotopoulou et al., 2018; Triantaphyllou et al., 2015; Vaiglova et al., 2018; Wang et al., 2019; Whelton et al., 2018).

Although the potential of strontium analysis to track mobility in the central Aegean has been adequately described in relation to the geographical patterning of strontium isotopic signatures (Nafplioti, 2011), the same paper also drew attention to inherent limitations associated with such applications. When overlooked, these limitations can lead to serious shortcomings in archaeological interpretation. Drawing examples from published strontium isotope research in this context, common pitfalls are flagged up with the intention to help strontium isotopic research in Aegean Archaeology to move forward.

A major common shortcoming in research of this kind in the Aegean and also more broadly, concerns the interpretation of what appear to be 'local' strontium values as evidence for the absence of mobility (in relation to this see also Snoeck et al., 2016: 403). To find that the strontium isotope signatures from the human or animal individuals examined are similar to the local bioavailable strontium values and also compatible with the local geology where they were recovered from, does not necessarily imply that those individuals were born and raised locally. Unless there is a clearly defined hypothesis where the specific individuals tested are thought to be non-locals, based for instance on material culture, mortuary architecture or other evidence, and unless the sites/regions under investigation separate clearly in terms of their local bioavailable strontium signatures (as in Nafplioti 2008, 2009b, 2012b), simply to show that the human signatures are compatible with local strontium isotope values does not say anything conclusive about the origins of the people tested. If the sites/regions investigated do not separate in terms of the locally bioavailable strontium signatures, it is possible that at least some of the individuals that appear to be 'locals' may in fact be non-locals, coming from different regions that are geologically and isotopically similar to the site where they were buried. A strontium isotope ratio study is meaningful only when it investigates relocation between geologically and isotopically different sites/regions. If there is not sufficient variation, any mobility will go unnoticed and the strontium isotopic results may be erroneously interpreted as evidence for either insignificant mobility or no mobility at all.

Equally, high variation in human enamel strontium isotope signatures does not necessarily equate to relocation and the presence of people of different provenance. If there is high variation in the signatures of the underlying geology this can potentially show on variable human tooth strontium signatures too as a result of differential access to the available feeding territories/production zones between people of the same community, or due to a potential maximization of the exploitation of the available arable land perhaps linked to population growth, as for instance Nafplioti and colleagues argued in their study of the site of Sissi on Crete (Nafplioti et al., 2021).. In addition, 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 (Ezzo, 1994: 7; Montgomery and Evans, 2009: 125).

It is therefore evident from the above that a systematic characterization of the bioavailable strontium isotope ratio variation for any region under investigation and a clear understanding of what 'local' signatures actually stand for in the specific context are imperative to achieving sound archeological interpretations. In addition, these should be coupled with a deep knowledge of the socio-economic background of the study including land-use and animal husbandry practices, as well as informed by archaeological theory. Otherwise, false claims on provenance and mobility or the absence of it are possible, and also research on mobility is relegated to a confirmation that it did happen or not, rather than elucidating its motivations, logistics and consequences to the lives of all those affected by it (Cabana 2011, van Dommelen 2014). In cases where there is not enough variation in the strontium isotope ratios between the sites under investigation and the potential of strontium isotope research is compromised, different isotopes preferably applied as a combination of more than one isotope system (e.g. oxygen, sulphur and hydrogen isotope ratios) in addition to strontium, including dietary isotopic data (e.g. carbon and nitrogen isotope ratios), can prove to be more informative in relation to past people's provenance and residential mobility, than strontium isotopes alone (e.g. Chenery et al., 2009; Fernandez-Crespo et al. 2020).

Sample size is also critical but often overlooked in data interpretation. For instance, samples in the order of a couple of dozens are simply not large enough to characterize mobility from mortuary contexts that were used over a few hundreds of, or even a thousand, years, as is the case, for instance, with the Early Minoan – Middle Minoan tholos tomb on Crete. Not to mention that statistical analyses may be unable to adequately describe differences in such contexts, owing to the very low, unrepresentative sample size.

Commingled assemblages are even more problematic, as it is difficult, if not impossible, to confidently identify and sample individuals that may represent first generation immigrants, which are at the focus of isotopic studies. Moreover, in multiple burials, lack of consistency in sampling the same skeletal element from all individuals may result in the duplication of certain people in the analyses.

Notwithstanding how vital the above recommendations are for securing higher standards for the associated research methodology, these alone will not suffice to advance the field. Rather in order to more effectively and systematically characterise past mobility and migration with a view to better understanding its motivations and consequences, we need to combine a methodologically sound research with a theoretically informed social bioarchaeology of migration.

Population movements are a recurrent theme in archaeological research. They have often been invoked as the cause or the effect, in other words, the start or end-point, in large-scale narratives involving culture change and discontinuity or economic and social transformations (Hakenbeck 2008; van Dommelen 2014). Paradoxically though, as phenomena in their own right, migration and residential mobility have received little attention. Research in this field normally identifies migration and mobility simply as events, rather than processes that need to be further characterized into their particulars. For instance, what is the size, composition or organization of the migrant group/s? Is there any identity negotiation and transformation for the individuals involved? What are the consequences for the host community or the one they left behind? Issues such as these have so far been overlooked in the relevant scholarship.

Inspired by recent social and anthropological work on contemporary migration and relevant archaeological discourse on the subject (e.g. Anthony 1997; Burmeister 2000; Hamilakis 2016), this paper proposes that the way forward for research in past residential mobility is to move beyond a mere fingerprinting of migration/relocation episodes, towards an investigation of these themes in the ancient world through a different paradigm, wherein the individual is central and migration and mobility are studied themselves as multilayered processes, as the author has put forward in her recent Marie Curie project, EPOCH GeoChem (Nafplioti, in preparation). For instance, who is moving? Under which circumstances? What are the consequences for the migrants and the host societies?

We need to move towards an archaeology of migration as a dynamic and complex social process that transcends simplistic categorisations, which fall short of reflecting past realities and human behaviour (Anthony 1990, 1997; Burmeister 2000, Cabana 2011; Gregoricka 2021). When investigating past mobility and migration, we need to advance from bimodal categorizations and dichotomous models of mobility such as mobile versus sedentary, or local versus nonlocal, to addressing the nuances of mobility through the incentives/motivation for it, the temporal and geographical scale, and structure of the group involved, including their age, gender, status and other aspects of their identity (Cabana and Clark, 2011; Campbell and Crawford 2012; Frieman et al. 2019; Gregoricka 2021; Nawyn 2010; Wendrich and Barnard 2008). By creating new knowledge on the origins, the lifeways and social organisation of the population/s examined using the remains of the people themsleves, research will advance from a mere fingerprinting of migration episodes by giving direct new insights into the 'how' and 'why' of mobility at specific times and places in prehistory that are not possible through other archaeological evidence alone. By doing so we can begin to move towards a social bioarchaeology of mobility and migration that acknowledges the variability and fluidity of mobile behaviours and offers more meaningful interpretations for it.

6. CONCLUSIONS

Despite more recent methodological advances in the field of isotope ratio analysis of archaeological remains, which have improved our ability to identify both short- and long-term residential mobility in the past and enabled us to move beyond a dichotomous classification of past individuals as either local or nonlocal, in research of this kind in the Aegean but also generally, there are still shortcomings we need to overcome, particularly with regard to research planning, sampling, data analysis and interpretation.

Yet, in order to more effectively and systematically characterise past mobility and migration with a view to better understanding the complexity of these processes, the motivations and consequences to the people moving, the receiving communities as well as those staying behind, we need to combine a methodologically sound research with a theoretically informed social bioarchaeology of migration. The way forward for strontium isotope research is to move beyond a mere fingerprinting of migration or relocation episodes, towards an investigation of these themes in the ancient world through a different paradigm, wherein the individual is central and migration and mobility are studied themselves as multi-layered processes and socio-cultural phenomena. Further, in this way, insights into relocations in the past, past lifeways and social organization gained though archaeological research, can also be applied to better understand contemporary large- and small-scale human movements, while all new knowledge on human mobility and migration generated from past and contemporary research can cross-fertilize the relevant fields involved.

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