Manuscript Details

Manuscript number	JASREP_2018_319
Title	From texts to teeth: A multi-isotope study of sheep and goat herding practices in the Late Bronze Age ('Mycenaean') polity of Knossos, Crete
Short title	From texts to teeth: caprine herding at 'Mycenaean' Knossos, Crete
Article type	Research Paper

Abstract

Abstract Linear B administrative documents of the late second millennium BC from urban Knossos, Crete, reveal that spatially extensive and centrally monitored sheep flocks and wool production played a fundamental role in Mycenaean palatial economy. Here we employ multi-isotope ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $87\text{Sr}/86\text{Sr}$) analysis of sequentially sampled sheep and goat tooth enamel bioapatite to explore life histories of animals consumed at Knossos. Interpretation of isotopic results incorporates new baseline data on bioavailable $87\text{Sr}/86\text{Sr}$ ratios from Cretan plants collected in relevant zones. Results reveal a variety of herding regimes, including seasonal ('wet/winter' to 'dry/summer') vertical movement of sheep from lowland to highland locations, more restricted mobility for goats in lowland to mid-altitude territories, possible input of fodder to goat diet, and exploitation of a range of plant ecosystems. Results broadly match documentary evidence and ethnographic/ecological expectations for sheep and goat herding at varying scales and underline the role of Knossos in mobilising resources from a range of herding systems and territories.

Keywords	$\delta^{13}\text{C}$; $\delta^{18}\text{O}$; $87\text{Sr}/86\text{Sr}$; Linear B; Knossos; animal mobility.
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Suggested reviewers	Dimitra Mylona, John Bennet, Jane Evans, Marie Balasse, Diamantis Panagiotopoulos
Opposed reviewers	Argyro Nafplioti

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Cover Letter

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Abstract

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Keywords

$\delta^{13}\text{C}$; $\delta^{18}\text{O}$; $^{87}\text{Sr}/^{86}\text{Sr}$; Linear B; Knossos; Sheep; animal mobility; 'palatial' economy

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Acknowledgements

The authors would like to thank the excavators and the British School at Athens for their support in sampling the archaeological material; Angelos Gkotsinas for his assistance with archaeological faunal and modern plant sampling on Crete in 2013; Chris Day (Department of Earth Sciences, University of Oxford) for his help with carbon and oxygen isotope analyses; Lucy Lawrence for assisting with enamel sampling; Eleni Nodarou (INSTAPEC) and Christoph Siart (University of Heidelberg) for providing materials for the compilation of the geological maps; John Bennet (British School at Athens) for reading and commenting on an earlier draft. John Bennet and Yannis Papadatos (University of Athens) provided additional references. Permission for sampling of archaeological material was granted by the Greek Ministry of Culture. The project was funded by the European Research Council (AGRICURB project, Grant No. 312785, PI Bogaard), the John Fell Fund, University of Oxford and a Fitch Laboratory (British School at Athens) Environmental Bursary.

Declaration of interest: None

Files submitted contain

- Manuscript with title with embedded tables 2-4. Table 1 is not embedded in the text because of its large size
- Figures 1-10, of which graphs are also available in Excel format
- Figure captions are provided in a separate .docx file
- Bibliographic references may also be re-formatted if necessary (original file available in Endnote x7)
- Components of figure 5 are available in higher resolution, as TIFF files if required
- Tables with supplementary data (S1, S2, S3, S4 and S5).

From Texts to Teeth

Highlights

- Documentary evidence from Mycenaean Knossos attests to palatial monitoring of large-scale sheep herding and wool production
- The large faunal assemblage from this period at Knossos offers a unique opportunity to evaluate textual evidence against the life histories of animals consumed at the site
- Multi-isotope analysis combined with sequential sampling of sheep and goat tooth enamel reveals different herding regimes for sheep and goats
- Results indicate seasonal vertical movement of sheep between lowlands and uplands, while goats were kept on a smaller scale within a narrower altitudinal range and perhaps foddered
- This is the first direct evidence that animals consumed at 'Mycenaean' Knossos reflect herding regimes indicated in Linear B records

From texts to teeth: A multi-isotope study of sheep and goat herding practices in the Late Bronze Age ('Mycenaean') polity of Knossos, Crete

3

1. Introduction

Control of livestock and their products, particularly wool for fine textiles, was central to the political economy of the Mycenaean 'palaces' of Late Bronze Age Crete and the southern Greek mainland (Killen, 2008). Records of sheep and other domestic animals make up a high proportion of Linear B administrative texts found in the palaces and especially at Knossos on Crete (e.g. Killen, 1993a). The texts provide a wealth of otherwise inaccessible information on numbers of animals of different species, their age and sex composition, their 'yields' (or perhaps rather contributions to the palaces) of offspring and wool, and their location (at least for administrative purposes) in the landscape. Nevertheless, ethnographically-informed consideration of the practicalities of animal husbandry (in particular, reproduction and mortality rates) and comparison with Late Bronze Age zooarchaeological data from the same regions, make clear that the surviving Linear B texts document only a few points in the life-cycles of selected categories of animals – presumably those of greatest interest to the palace administrations (Halstead, 2002). The conventional macroscopic zooarchaeological record is potentially less selective than Linear B texts, representing animals overlooked by palatial administrators as well as those that they documented, but is also limited in shedding light primarily on where and how animals were finally discarded (usually after slaughter for consumption) and only rarely on earlier stages of their lives.

Longer-term records of animals' diets and movements can be unlocked by isotopic analysis of their bones and teeth. Here we explore the potential of stable carbon ($^{13}\text{C}/^{12}\text{C}$, $\delta^{13}\text{C}$), oxygen ($^{18}\text{O}/^{16}\text{O}$, $\delta^{18}\text{O}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotope ratios in dental enamel bioapatite to enrich our understanding of animal husbandry, and thus palatial political economy, in the case of Late Bronze Age Knossos on Crete. We analysed modern plants from localities associated with the ancient Knossos polity to establish area-specific $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. From Knossian contexts, contemporary with the major Linear B archives (LM IIIA, ca. 1430-1390 BC – Shelmerdine, 2008, 3-7, figure 1.2), we sequentially sampled enamel bioapatite of sheep and goat teeth and

measured $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values. We interpret results in light of archaeological, zooarchaeological and ethnographic evidence with the aim of exploring sheep and goat management strategies during the Final Palatial (FP) period (date) on Crete and, more generally, of evaluating the potential of such approaches to shed light on ancient economies.

2. Knossian caprine management and political geography: insights from texts, archaeology and ethnography

The Linear B sheep records from Knossos distinguish animals by sex and age (e.g., lambs, yearlings, old sheep). The largest group of such texts, the Knossos D-series (and particularly the Da-Dg and Dn sets), records numerous sheep ‘flocks’ of 30-400 head, dominated more or less heavily by males that have been interpreted as probable wool-producing castrates or ‘wethers’, as known from specialised wool flocks on English medieval estates (Killen, 1964). Consistent with this interpretation, other documents record targets for and fulfilment of wool deliveries, while the archives imply limited palatial interest in carcass (meat, sinews, horn and skins) or dairy products. Records of *reproductive* flocks (consisting of breeding females and their young), that might have replaced lost or culled wool sheep, are much scarcer and indeed far too few to re-stock the recorded wool flocks (Halstead, 2002; Killen, 1993a). Equally, although a few individual sheep are recorded as being ‘finished’ and/or destined for feasting or sacrifice (e.g. the Dm set, Halstead, 2002, 156; Killen, 1999), the eventual fate of the vast majority of the animals (e.g. were they consumed at major centres including Knossos?) is unclear. In terms of overall scale, the Da-Dg and Dn texts record ca. 66,000 wool sheep under Knossian scrutiny (Halstead, 2002, 154; Olivier, 1967, 82), while inclusion of ‘inferred’ but unrecorded breeding stock and of animals recorded as ‘missing’ (that herders were expected to replace, presumably from their own stock – Halstead, 1999a) would raise this total to approximately 156,000 head during any one year (Halstead, 2002, 159, table 2). These constitute a sizeable population, requiring extensive areas of pasture.

Records of goats are much less frequent. Some sizeable (40-230 head), single-sex herds (predominantly females) are listed in texts of the C-series (Halstead, 2001, 157), while modest numbers of females (7-30), whose role is unclear (perhaps breeding

65 stock, milk producers or destined for feasts/sacrifices), are listed as contributed by
 66 individual communities (Halstead, 2001, 162). The total recorded number of goats
 67 administered by Knossos comes to more than two thousand annually (Halstead, 2001,
 68 159, table 2).

69 Flocks are listed against toponyms, most likely of settlements (Bennet, 1985, 235;
 70 2011, 140), providing, *inter alia*, important insights into the extent of the territory of
 71 the FP Knossos polity, which appears to have extended as far as the Isthmus of
 72 Ierapetra to the east and perhaps as far as Apokoronas to the west (Figure 1). This
 73 amounts to ca. 4-5,000 km² or about half to two thirds of the island (Bennet, 2017)
 74 and embraces a range of coastal and inland low-lying plains: Knossos' own hinterland
 75 (Bennet, 1985, 237), Karteros and Malia (perhaps Linear B *se-to-i-ja* – Bennet, 1985,
 76 243) to the east, Herakleio and Rethymno (perhaps *da-*22-to*) to the west, and the
 77 Mesara and perhaps the Amari valley to the south and southwest. It may also have
 78 included three upland areas with extensive plateaux: Lasithi and Katharo to the east
 79 and the Psiloritis range to the west. The archives are more or less silent about these
 80 latter apart perhaps from the mention of 'Lasynthos', possibly a settlement on the
 81 Lasithi plateau (Bennet, 1985, 240). The Knossian territory appears to have been
 82 controlled directly from Knossos and through secondary centres such as *pa-i-to*
 83 (below), while the Chania region, in the far west of the island, seems to have been
 84 controlled more loosely and indirectly (Bennet, 1985).

85 Wool flocks are associated in the archives overwhelmingly with central Cretan
 86 locations (Killen, 1977), but few of the place-names can be firmly linked to known
 87 archaeological sites (Bennet, 2011, 144). In the D-series these include, apart from
 88 Knossos, *su-ki-ri-ta* (probably Syvrita in the Amari – Bennet, 1990, 199), *tu-ri-so*
 89 (Tyliisos – Bennet, 1985, 245), and *pa-i-to* and *da-wo* in the Mesara, probably
 90 Phaistos and perhaps Agia Triada, respectively, although the latter identification is
 91 still debated (Privitera, 2014, 440). A large group of 11,600+ lambs (tablet Dn 1319,
 92 ostensibly by far the largest record of young replacement stock), is associated with *a-*
 93 *mi-ni-so*, perhaps Amnissos (Olivier, 1967, 81), at the eastern end of the bay of
 94 Karteros (Figure 1). Settlement in upland areas is more poorly known
 95 archaeologically for this period, but sites like Plati on the Lasithi plateau (Dawkins,
 96 1913/14; Watrous, 1982) and Zominthos on Mt Psiloritis (Sakellarakis and

97 Panagiotopoulos, 2007, 192, footnote 8) (Figure 1) testify to occupation, if not direct
 98 links with the palatial centre.

99 In the recent past on Crete, the larger herds of goats and especially flocks of sheep
 100 tended to spend the winter grazing stubble and fallow fields (e.g. in the Mesara) or
 101 rough scrubland (e.g. around Malia) in the lowlands and the summer in and around
 102 upland basins, such as Nida (in the Psiloritis range) and the Lasithi Plateau, to take
 103 advantage of complementary seasonal differences in the abundance and quality of
 104 pasture. A similar regime has tentatively been considered for the Late Bronze Age,
 105 given the number and size of flocks and their apparent concentration (at least for
 106 administrative purposes) in areas with extensive arable potential and so perhaps
 107 seasonal stubble/fallow grazing (Halstead, 1981, 204; Killen, 1964, 5). Traditionally
 108 on Crete (e.g. Mavrakakis, 1948, 37), as in mainland Greece, large herds were often
 109 subdivided so that, for example, lactating females grazed better pasture than ‘barren’
 110 stock with lower nutritional requirements, and the apparently separate flocks of
 111 distinct age and sex composition, recorded in the Linear B texts, raise the possibility
 112 that livestock were subject to different mobility and feeding routines at different ages.
 113 On a smaller scale, textual references to finishing (o-pa) for consumption (Killen,
 114 1999), albeit without clarification as to how this was achieved, imply that some
 115 animals were selected for fodder supplements or particularly high-quality pasture.

116 Although the Linear B archives provide a wealth of detail on the management of
 117 sheep and other livestock, they overlook many animals entirely and shed only
 118 selective light on the remainder. Moreover, the toponyms associated with the large
 119 wool flocks, whether these served to locate the named ‘herder’ or the recorded sheep,
 120 certainly do not indicate whether the latter (and perhaps likewise goats) made
 121 seasonal use of upland pastures (Bennet, 1985, 237 n.19). The present study attempts
 122 to clarify the degree of mobility of sheep and goats consumed at FP Knossos, the
 123 extent to which any such mobility involved seasonal use of pastures at different
 124 altitudes, and whether any additional variability in animal diet might be linked to the
 125 enigmatic finishing of livestock for consumption that is recorded textually.

126

127 **3. Methods**

128 *3.1. Strontium isotopes in the Cretan environment*

Water-soluble strontium is taken up by plants from the soil and atmospheric sources (e.g. Graustein, 1989) and then transmitted through the food chain without further alteration (Blum et al., 2000). In animals (including humans), this *bioavailable* strontium is gradually incorporated in trace quantities in tooth enamel during mineralisation (Section 4.2.1). Tooth enamel $^{87}\text{Sr}/^{86}\text{Sr}$ ratios thus reflect the sources consumed during mineralisation and their determination in archaeological teeth is used to reconstruct mobility patterns of humans and, increasingly, other animals (e.g. Balasse et al., 2002; Copeland et al., 2016; Gron et al., 2016).

Soil $^{87}\text{Sr}/^{86}\text{Sr}$ ratios mainly reflect those of parent bedrock, which in turn reflect the latter's original Rb/Sr ratios and age (e.g. Copeland et al., 2011), but are also affected by any subsequent metamorphism (Bickle et al., 1988, 1997; Satish-Kumar et al., 2008). Crete, located in a tectonically highly active region, is geologically complex, comprising sedimentary and igneous formations of variable age (some subsequently metamorphosed) that recur across the island (Figure 1). Upland massifs are dominated by older (Upper Carboniferous to Palaeocene) marine sedimentary rocks and lowlands by much younger (Neogene to Pleistocene), mainly marine sedimentary formations (Fassoulas, 2000; van Hinsbergen and Meulenkamp, 2006; Kiliass et al., 1994; Kneuker et al., 2015; Papanikolaou and Vassilakis, 2010; Romano et al., 2004).

A key region for the present study (Table 1), the wider Knossos area and its possible Bronze Age agricultural catchment including the Herakleio and Karteros coastal plains (Whitelaw in press), is dominated by Neogene calcareous marine sedimentary rocks, mainly marls and limestones, locally overlain by Holocene-Pleistocene alluvia/colluvia (Figure 1, inset C). Of the sampled uplands (Table 1, Figure 1, insets B and D), Mesozoic platy limestones of the Plattenkalk Unit form the western part of the Psiloritis massif and Tripolis Unit limestones and flysch its eastern part (Figure 1, inset B), while Tripolis Unit rocks combine with the Palaeozoic Phyllite-Quartzite Unit in the Lasithi massif (Figure 1, inset D). Phyllites are affected by Oligocene-Eocene metamorphism (Zulauf et al. 2016, 1903). Karstic depressions on the upland limestones are filled by probably much more recent alluvial, colluvial and aeolian sediments (Siart et al., 2010). Igneous rocks of the Uppermost Unit, such as ophiolites and granodiorites, occur mainly in central-southern Crete and the Mirabello area, respectively (Figure 1, insets C and D, respectively). For the structurally and geologically complex ophiolitic 'nappes', recent direct dating (to the Jurassic and

Cretaceous) of some components and measurement of their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (e.g. Koepke et al., 2002; Koepke and Seidel, 2004; Tortorici et al., 2012) are most useful for the present study (Section 5.1, Table 2).

Geographical region	Source type (geological formation; atmospheric/airborne)	$^{87}\text{Sr}/^{86}\text{Sr}$ ^a	Source
Herakleio basin: Kroussonas and north of Ambelouzos	Messinian (Neogene) fossils	0.7089-0.7090	Mertz-Kraus et al., 2009, fig. 1; table 1
North-west of Kato Asites			Brachert et al., 2015, 268
S Sicily	Tortonian (Neogene)	0.7089	Sprovieri et al., 2003
Israel, various locations	Neogene	0.7079-0.7084	Hartmann and Richards, 2014, table S3
Various locations	Cretaceous marine limestones	0.7072-0.7077	Koepnick et al., 1985, appendix I; Jones et al., 1994, fig. 2)
Various locations	Jurassic marine limestones	0.7068-0.7078	Jenkyns et al., 2002, fig. 11
Various locations	Triassic marine limestones	0.7071-0.7085	Koepnick et al., 1990, appendix B; Song et al. 2015, table S1
Various locations	Late Permian marine limestones	0.7068-0.7075	Song et al., 2015, table S1
Mirabello, east Crete	Upper Cretaceous granodiorites (whole rock values)	0.7033-0.7060	Langosch et al., 2000, 340, table 2; Kneuker et al., 2015
Israel, north coastal plains	Rainfall	0.7090-0.7092	Herut et al., 1993, fig. 1, table 1
Sea south of Crete	Central Saharan (Pre-Cambrian rocks) airborne sediments from surface sea-bottom sediments	0.7209	Krom et al., 1999, 323, fig. 1
Global	Sea water (modern)	0.7091	Burke et al., 1982, table 1

Table 2. Summary table of published $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from geological and atmospheric sources relevant to the present study.

^a Figures rounded to the closest fourth decimal point.

Although soil $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are more heavily influenced in drier regions by those of the underlying bedrock than atmospheric input (Hartman and Richards, 2014, 262), the derivation of bioavailable strontium from atmospheric sources, as well as geological substrates, has important implications for interpreting $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in living organisms in terms of geographic provenance. As regards atmospheric sources, precipitation is likely to contain strontium with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios close to those of modern seawater, especially in coastal areas affected by sea-spray (Table 2). Consistent with this expectation, the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of rainfall from coastal stations in northern Israel is identical to that of modern seawater (0.7091, Table 2). For Crete another documented atmospheric source is particles transported from the Sahara in dust storms (e.g. Ganor and Mamane, 1982; Moulin et al., 1998) with an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7209 (Table 2). Atmospheric sources are thought to contribute more bioavailable Sr than underlying bedrock to plants growing on rendzina soils (e.g. Hartman and Richards, 2014, 262), which are common over the

Neogene marine formations around Knossos and Karteros (Figure 1). Similar effects may be expected on fine sediments infilling upland karstic features.

Moreover, in the case of Crete, processes such as metamorphism and exposure of different parts of the sequence of sedimentary formations due to erosion and tectonic activity and the rarity of direct measurement and dating of exposed formations makes extrapolating $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from assumed contemporary rocks from distant regions rather problematic. Different parts of these sedimentary sequences, exposed locally by erosion and tectonics, have rarely been directly measured or dated so that age and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have often, problematically, been extrapolated from distant formations assumed to be contemporary. In addition, bio-available Sr taken up by plants and then herbivorous animals is significantly affected, in some localities and on some substrates, by atmospheric inputs. For these reasons, this study relies primarily on direct measurements of Sr ratios in plants in targeted topographic and geological settings.

Here we measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in modern plants, both ligneous (deep-rooting) and non-ligneous (shallow-rooting), from regions of relevance to the Knossian polity and political geography as inferred from Linear B texts (Section 2). Due to their different rooting depths, it is expected that ligneous plants will predominantly reflect underlying bedrock and non-ligneous plants atmospheric input. Thus ligneous and non-ligneous plants in combination provide a broader overview of bioavailable strontium than does either category in isolation (e.g. Bogaard et al., 2014; Evans et al., 2010; Hartman and Richards, 2014; Kootker et al., 2016). The values obtained from plants are used below to interpret those acquired from sequential sampling of archaeological sheep and goat tooth enamel, in a first attempt to reconstruct mobility patterns. The likelihood of so detecting seasonal or longer-term movement will, however, depend on the degree of difference in bioavailable Sr between the various grazing/browsing areas used by each animal during the period of tooth enamel formation. Because ligneous plants are more likely than non-ligneous to reflect underlying bedrock, it should also be noted that the prospects of detecting movement in this way may be greater in browsers (e.g. goats) than grazers (e.g. sheep).

To date, the only available $^{87}\text{Sr}/^{86}\text{Sr}$ baseline ratios from Crete derive from a few measurements of modern land snails, as well as a single modern and a few

archaeological domestic animal bones (Nafplioti, 2008, table 3; 2011, table 1). These proxies were avoided in the present study. Land molluscs because of their diet and physiology provide very localised values and, like non-ligneous plants (below), tend to reflect mainly the atmospheric contribution to bioavailable strontium (Evans et al., 2010, 3; Hartman and Richards, 2014, 259). Mammalian herbivores have a more extensive feeding range, but it is unknown *a priori* whether archaeological specimens belong to animals born and raised locally. Finally, the absence of wild and restricted range of feral mammals in remote upland areas and the widespread use of industrial feeds for domesticates render collection of adequate modern faunal samples logistically complicated and beyond the scope of the present study.

3.2. Stable oxygen isotope ratios: methods and background to Cretan climate

The $\delta^{18}\text{O}$ values of tooth enamel bioapatite are used here to shed light on potential *seasonal* mobility of animals and also to establish a seasonal temporal framework to inform interpretation of $\delta^{13}\text{C}$ values. $\delta^{18}\text{O}$ values reflect that of body water, which in large mammals from temperate Europe is strongly related to the $\delta^{18}\text{O}$ value of ingested, local meteoric water, comprising both drinking water and that contained in ingested plants (D'Angela and Longinelli, 1990; Longinelli, 1984). The $\delta^{18}\text{O}$ value of meteoric water varies according to a combination of climatic and geographic factors, including ambient temperature, amount of rainfall, and altitude (Bar-Matthews et al., 1999, 2003; Dansgaard, 1964; Gat, 1996). Thus, at high and middle latitudes, there is seasonal variation in $\delta^{18}\text{O}$ values, which are lower during the cooler/wetter (November-April) and higher in the hotter/drier months (May-October) (Rozanski et al., 1993). $\delta^{18}\text{O}$ values in precipitation are lower at higher altitudes (Giustini et al., 2016; Gonfiantini et al., 2001; Longinelli and Selmo, 2003) by on the order of 0.15–0.5‰/100 m of elevation (Longinelli and Selmo, 2003; Siegenthaler and Oeschger, 1980). Sequential analysis of $\delta^{18}\text{O}$ values along the growth axis of a tooth can therefore reveal a seasonal cycle over the period of tooth enamel formation (Fricke and O'Neil, 1996). Under a Cretan climatic regime, a sheep or goat ranging year-round within the same locality should thus exhibit a marked increase in $\delta^{18}\text{O}$ values from the wet/cool to the dry/hot season, whereas an animal moving from lowland

winter to upland summer pastures (potentially 1000-2000 m higher and 6°C cooler – Figure 2, Suppl. Table S1) should exhibit a dampened seasonal cycle.

3.3. Stable carbon isotope ratios: methods and background to Cretan vegetation

The $\delta^{13}\text{C}$ value of tooth enamel carbonate reflects that of the *whole* diet (Lee-Thorp et al., 1989; Ambrose and Norr, 1993). The main factor influencing $\delta^{13}\text{C}$ values of terrestrial plants is their photosynthetic pathway, with modern C_3 plant $\delta^{13}\text{C}$ values averaging c. -27‰ (with values in xeric habitats as high as -22.6‰) and values for C_4 plants averaging c. -12.5‰ (Hartman and Danin, 2010, table 1; O’Leary, 1988; van der Merwe and Medina, 1989). Plant $\delta^{13}\text{C}$ values will be slightly higher (approximately 2‰) for the archaeological contexts relevant to the present study (ca. 1400 BC) than modern values, due to the recent input of ^{13}C -depleted carbon into the atmosphere from burning of fossil fuels (Friedli et al., 1986). Enrichment in ^{13}C of c. 11.5-15.4‰ has been measured between diet and enamel bioapatite in sheep (Zazzo et al., 2010), which is similar to values calculated for cattle (Balasse, 2002; Passey et al., 2005, 1467) and large wild ruminants (Cerling and Harris, 1999, 356, table 1); Makarewicz and Pederzani (2017, 6) suggest an enrichment value of 12‰ for sheep.

The Cretan native flora is dominated by C_3 plants growing mostly in open conditions; dense forests are lacking, especially in central Crete, and scrub (phrygana and maquis) communities are very extensive (e.g. Vogiatzakis and Rackham, 2008). In coastal (rocky, sandy and marshy) environments, communities are composed of both C_3 and C_4 species, including halophytes (e.g. *Salsola kali*, *Crithmum maritimum*), which are expected to display elevated $\delta^{13}\text{C}$ values due to salinity (e.g. O’Leary, 1988, 333).

There is no palaeoenvironmental evidence that ‘natural’ vegetation was radically different, especially in the FP period (Vogiatzakis and Rackham, 2008, 257). On cultivated land, ruderal communities dominated by C_3 species are well documented (e.g. Bergmeier, 2006; Bergmeier et al., 2001, 352; Bergmeier and Strid, 2014; Turland et al., 2004) and have traditionally been a focus for grazing by sheep and goats, while C_4 plants can be encountered from late spring through to early autumn among summer crops, in irrigated vegetable gardens (e.g. *Portulaca oleracea* – purslane, *Cynodon dactylon* – Bermuda grass; Bergmeier, 2008), and (at least in wetter years) after harvesting of winter crops. Plants from the above communities are

documented archaeobotanically from Neolithic to FP contexts on Crete (Livarda and Kotzamani 2013, table 3; Livarda, pers. comm.). Finally, the growing later Bronze Age archaeobotanical dataset of cultivated cereals and pulses comprises exclusively C_3 species (the millet reported in Livarda and Kotzamani, 2013 is most likely intrusive – Livarda, pers. comm.).

Coupled with $\delta^{18}O$ values for the same samples, incremental $\delta^{13}C$ values for sheep and goat teeth may reveal seasonal or other temporal variation in the diet of these animals (e.g. Balasse, 2002). In C_3 plants, differences in $\delta^{13}C$ values relate to the rate of passage of carbon dioxide (CO_2) through stomata, regulated by water availability (Ehleringer et al., 1993; Farquhar et al., 1989). Thus, C_3 plant $\delta^{13}C$ values are strongly correlated with environmental factors such as precipitation, relative humidity and light intensity (Bonafini et al., 2013; Broadmeadow and Griffiths, 1993; Tieszen, 1991; Wallace et al., 2013). In eastern Mediterranean Israel, under climatic conditions analogous to those of Crete (with average annual rainfall of c. 500 mm in the central lowlands – National Observatory of Athens records for 2010-2017, <http://meteosearch.meteo.gr/>), C_3 plant $\delta^{13}C$ values rise by c. 1–2‰ from the wet-cool (November-April) to dry-hot (May-October) season (Hartman and Danin, 2010), with such seasonal variation apparent in both the ligneous bushes and trees favoured by goats and the herbaceous vegetation preferred by sheep (Leavitt and Long, 1986; Leavitt and Long 1991). In addition, due to changes in temperature and atmospheric pressure, $\delta^{13}C$ values of C_3 plants increase by approximately 1.2‰ per 1000 m of altitude gained (Körner et al., 1988, table 3; 1991), while they also appear to be about 1-2‰ higher year-round for browsed shrubs and trees (wet -27‰, dry -25‰) than grazed annuals and forbs (wet -29‰, dry -26‰) (Hartman and Danin, 2010, 845 fig. 4a, b, e).

Given the dominance of C_3 plants in the Cretan flora, if animals fed on natural vegetation, we would expect C_3 -type values (c. -28 to -22‰ – O’Leary 1988), albeit elevated because of the climate and open vegetation, while a value of -13.7‰ for C_4 *Cynodon* is provided by Passey et al. (2005, 1461). If, consistent with their natural dietary preferences, sheep tended to graze and goats to browse, $\delta^{13}C$ values should also be slightly higher for the latter species and, in either case, values for both species should be higher in the dry/hot than wet/cool season. Conversely, potential reasons for $\delta^{13}C$ values not rising and falling in tandem with $\delta^{18}O$ include winter grazing on

coastal rough pasture rich in C₄ plants/halophytes or provision of fodder harvested in a different season. Sheep and goats are pastured on coastal rough grazing (containing C₃ halophytes and some C₄ species) on Crete today and this was even more common in the recent past (Halstead and Isaakidou, fieldnotes) (Figure 3), as elsewhere in the eastern Mediterranean (El Shaer and Attia-Ismail, 2015; le Houerou, 1994).

Linear B texts classify some animals as finished, without specifying how this was achieved. One obvious possibility is feeding of crop residues or surplus grain from the C₃ cereals and pulses attested archaeobotanically. Alternatively, at the mainland palaces of Pylos and Thebes, the commodity *171, recorded as fed to various livestock species (Halstead, 2002, 168), has tentatively been identified as *Cyperus* – perhaps *Cyperus esculentus* or *C. rotundus*, used in palatial manufacture of perfumed oil (Negbi, 1992), or *C. longus*, much sought after by free-range pigs in Greece (Halstead and Isaakidou, 2011, 171), and in either case a C₄ plant.

4. Sampling and laboratory methods

4.1. Modern plant sampling for ⁸⁷Sr/⁸⁶Sr baseline values

4.1.1. Sampling strategy

We analysed 69 plant samples (Table S1), from 36 localities (Figure 1, insets B-D), targeting where possible taxa normally consumed by sheep and goats. In each locality, ca. 50–100 g of ligneous (woody taxa, trees and shrubs, n=45) and non-ligneous (herbaceous perennial and annual plant species, n=24) plants were collected and sampling location coordinates recorded using a Garmin GPS unit. Each sample was analysed separately to test for variability in bioavailable Sr values in relation to rooting depth (cf. Hartman and Richards, 2014, 251). Care was taken to avoid areas where chemical fertilisers had been applied (cf. Price et al., 2002, 126) and to collect only renewable parts, i.e. leaves, stems and fruits. Samples were collected in late October-early November 2013 (at the end of a severe drought season), in summer 2014, and in early April 2015. Possible influence of season and year of collection on results is considered below.

The choice of localities was dictated by archaeological, ethnographic, geomorphological and geological criteria. We sampled the following localities: (a) the wider Knossos valley, including Mt. Juktas at its head; (b) areas with distinct igneous

geology (Mirabello and Aghios Georgios Epanosiphi Monastery); (c) the vicinity of secondary palatial administrative centres (e.g. Amnisos, Tylissos); (d) upland massifs, where recent large-scale transhumant herding of sheep and goat flocks is ethnographically attested (Lasithi and Psiloritis). An ideal sampling strategy would have involved a continuous transect from the Herakleio coast through its coastal plain (the immediate agricultural catchment for Knossos), south to Knossos and further inland to monitor the geographic extent of the effects of sea-spray on Sr values, but Herakleio urban sprawl has extensively obliterated natural plant habitats. Instead, the Karteros coastal plain north-east of Knossos was selected for its topographic, geomorphological and geological affinity to the Herakleio plain; samples were collected along a N-S transect, following the valley of the modern Karteros stream. Finally, it was not possible for logistical reasons to sample the Mesara, Crete's largest lowland arable plain, but its bioavailable Sr may not be significantly different to that of the geologically and geomorphologically similar Knossos and Karteros lowlands (e.g. Meulenkamp et al., 1994).

4.1.2. Laboratory procedures

Plant samples were oven dried at 40°C until fully dry. In the laboratory, plants were crushed in a freezer mill before c. 1 g was ashed in covered porcelain crucibles at 500° C for 6–8 hours in the Department of Archaeology, University of Cape Town. Approximately 50-100 mg of ash was transferred into Savillex™ beakers in a *class 100 (ISO 5)* clean lab facility. Each sample was digested in 2 mL of 14.3 M (65%) nitric acid (HNO₃) at 140°C. After digestion, the samples were left to dry overnight at 130° C and then re-dissolved in 2 mL 2 M HNO₃ and loaded into c. 800 µL Teflon columns containing pre-conditioned Eichrom Sr-spec pure resin (50-100 µm). After six washes with 2 M HNO₃, the Sr was eluted with 3 mL ultrapure deionised water, (after Pin et al., 1994), dried and re-dissolved in an appropriate volume of 0.2% HNO₃ to give ⁸⁸Sr signal intensities of 6–8 V. Sr isotopic measurements were performed with a Nu Instruments NuPlasma HR multi-collector ICP-MS instrument at the University of Cape Town. All analyses are referenced to bracketing analyses of NIST SRM987 using a ⁸⁷Sr/⁸⁶Sr normalizing value of 0.710255. All Sr isotope data were corrected for isobaric Rb interference on mass 87 using the measured signal for ⁸⁵Rb and the natural ⁸⁵Rb/⁸⁷Rb ratio. Instrumental mass fractionation of the measured

isotope ratios was corrected using the exponential law and a $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194 (Nier, 1938, as described in Harris et al. 2015). All samples were run to an internal precision of ± 0.000020 (2 SE) or better. Results for an in-house carbonate reference material (0.708917 ± 0.000022 ; $n=4$) analysed as an unknown with the enamel samples, and an in-house basaltic rock reference material (0.704898 ± 0.000034 ; $n=13$) agree with the long-term results for these materials from this facility (0.708907 ± 0.000023 ; $n=56$, and 0.704905 ± 0.000034 ; $n=56$, respectively). Total procedural strontium blanks were typically better than ~ 250 pg.

4.2. Sequential sampling of archaeological dental enamel for $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis

4.2.1. Sample selection

We selected specimens from closely dated contexts whose preservation allowed secure species identification and estimation of age at death. We sampled mandibles (and sets of matching loose mandibular teeth to increase available sample), with fully erupted mandibular second molars (M_2) at early stages of wear (age stages D and E of Payne, 1973) of three sheep and four goats. Species identification followed published macroscopic criteria (Halstead et al., 2002; Payne 1985). Adjacent third molars (M_3) were sampled from two of the same individuals (one sheep and one goat) to extend the observable age range. We chose teeth of this age stage for compatibility with earlier research and to combine results eventually with dental microwear data for the same specimens. This sampling strategy introduces limitations, however, and will be revised in future work (see Section 7). Tooth enamel bioapatite was sequentially sampled and analysed for determination of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Our selection criteria provide individuals slaughtered in their second and third years and teeth formed mostly post-weaning and preserving as long a sequence of an individual's life as possible. Observation of traditional breeds suggests that mandibular tooth crown development starts after birth (from ca. 1-2 months) and ends at ca. 12 months for sheep M_2 , and starts at ca. 11-12 months and ends between 18 and 24 months for M_3 (Mihaud and Nézit, 1991, quoted in Zazzo et al., 2010, 3574; Weinreb and Sharav, 1964, table 1). A study of Scottish feral goats suggests start of M_3 formation around 12 months and completion around three years (Bullock and

Rackham, 1982, table 3). It should be noted, however, that controlled studies show that tooth enamel takes 5–6 months to mineralise fully (Balasse et al., 2012; Zazzo et al., 2010), reducing the sensitivity of tooth enamel isotope values to changes in the isotope values of the diet and resulting in a time-averaged signal of isotopic changes. Moreover, various studies suggest that completion of M₃ development can vary by 4–6 months between individuals (e.g. Blaise and Balasse, 2011; Zazzo et al., 2010). Nevertheless, variability in measured isotopic values of both archaeological and modern specimens highlights the utility of measuring sequentially sampled tooth enamel bioapatite.

4.2.2. Laboratory procedures

The surface of each tooth cusp was cleaned by abrasion with a drill bit and between 14 and 23 samples of enamel powder were taken sequentially from the buccal side of the anterior lobe of each M2 and the buccal side of the central lobe of each M3 using a 1 mm diameter drill bit. Enamel samples weighing c. 400 µg were reacted with 100% phosphoric acid at 70°C for 240 seconds in individual vessels in an automated cryogenic distillation system (Kiel IV device) interfaced with a Delta V isotope ratio mass spectrometer, in the Department of Earth Sciences, University of Oxford. The tooth enamel bioapatite $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are expressed per mil relative to VPDB on a normalized scale such that the $\delta^{18}\text{O}$ of NBS-19 is -2.20‰ and the $\delta^{18}\text{O}$ of NBS-18 is -23.20‰ and the $\delta^{13}\text{C}$ of NBS-19 is $+1.95\text{‰}$ and the $\delta^{13}\text{C}$ of NBS-18 is -5.01‰ . The analytical precision within each run, calculated from four measurements of an in-house ostrich eggshell standard, varies from 0.08 to 0.09‰ for $\delta^{13}\text{C}$ and from 0.07 to 0.09‰ for $\delta^{18}\text{O}$. Enamel from only every second sample was analysed as this gave good enough resolution for our interpretations.

Three enamel samples from each tooth were also selected for $^{87}\text{Sr}/^{86}\text{Sr}$ ratio determinations. Each sample for strontium isotope analysis comprised three adjacent sequential samples (to give enough material for analysis) and their position on the tooth was selected so as to capture the maximum, minimum and mean $\delta^{18}\text{O}$ values. A test for contamination was carried out on amalgamated enamel samples from two teeth. These samples were repeatedly leached in buffered acetic acid, with the leachate being removed before the next leaching step. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the un-

leached enamel and leachates after one, five, ten, fifteen and twenty leaching steps were determined (Table S2). There was no significant difference between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the un-leached enamel and the successive leachates, so it was deemed unnecessary to pre-treat the enamel samples prior to strontium isotope analysis. The untreated enamel samples were digested in 2 mL of 14.3 M (65%) HNO_3 at 140°C . After digestion they underwent the same laboratory protocol as the modern plant samples.

5. Results and Discussion

5.1. Modern plant $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

5.1.1. Plants and geology

Table 1 shows $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of modern plants, which range from 0.70781 to 0.71043. Two values from non-ligneous plants (25c, Psiloritis-Nida; 29b, Lasithi) fall outside this range. Since these were not growing on distinct geological outcrops with potentially high values and the ligneous plants collected from the same localities did not produce similarly high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, we treat these data points as anomalies and exclude them from subsequent discussion.

Figure 4 shows $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the modern plants sampled, grouped by location and coded according to type and age of geological substrate. Plant samples from Knossos and Kartheros (KK), growing on rendzinas formed over Neogene marine sedimentary rocks and on Quaternary alluvia/colluvia mainly consisting of Neogene parent materials, have very homogeneous ratios of 0.7091 ± 0.00012 ($n=32$). Similar ratios were obtained from plants growing on comparable substrates at Tylissos (0.7092, $n=2$). These ratios are slightly higher than those of measured fossils from Neogene beds in the Herakleio basin and very close to modern sea-water and also rainfall ratios from stations on the coastal plain of Israel (Table 2), suggesting that, at KK and Tylissos, plants growing on rendzina soils as expected mostly derived Sr from atmospheric sources. Mirabello, the only other coastal location sampled, has values (0.7082 ± 0.00018 , $n=4$) lower than sea- and rain-water, even though samples were collected well into the rainy season (early April), perhaps because of the presence of less radiogenic Upper Cretaceous granodiorites among Mirabello Neogene formations (Table 2). The similarity of coastal Mirabello alluvium values to those from upland

Psiloritis and Lasithi alluvial/karstic formations (below) would pose problems of equifinality if $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were used in isolation to explore mobility.

Values for samples collected on older marine formations yielded a more complex picture. Plants growing on Tripolis Unit Cretaceous limestones of Mt Juktas provided values close to KK (0.7091 ± 0.00007 , $n=4$), rather than the lower values on Cretaceous limestones elsewhere (Table 2), again perhaps reflecting a predominantly atmospheric input. Due to its height and location, Juktas benefits from raised precipitation and our samples were collected in mid-spring, towards the end of the rainy season. Platy limestones and karstic features (Locality 23 doline and Nida polje, Table 1) on Psiloritis produced lower values (mean= 0.7085 ± 0.00018 , $n=5$) for plants collected at the end of the dry season, with a single exception, a non-ligneous plant sample (25b= 0.7095 ; Table 1). Values from similar alluvial features on Lasithi are mostly within the same range (0.7087 ± 0.00031 , $n=7$) and thus both upland basins are distinguishable, by significantly lower values, from localities in coastal north-central Crete (KK). Plants growing on Psiloritis Tripolis limestones (/dolomitic limestones/dolomites) yielded a broader range of values, one overlapping with KK (29a, Table 1). This breadth of values perhaps reflects the wide age range of Tripolis limestones (Upper Triassic to Upper Jurassic, according to IGME maps). Distinctly high values for plants growing on Upper Carboniferous-Middle Triassic phyllites-quartzites on Lasithi (0.7096 ± 0.00004 , $n=4$) partly overlap with those for Tripolis limestone and for Epanosiphi ophiolites (possibly Jurassic – Koepke et al., 2002, 198; Liati et al., 2004). The latter are not extensive, but highlight how distinct geological substrates can yield quite variable values at inland locations.

Thus, our analysis of modern plant $^{87}\text{Sr}/^{86}\text{Sr}$ across central and east-central Crete revealed that, despite the great complexity of Cretan geology and hence *bedrock* $^{87}\text{Sr}/^{86}\text{Sr}$, the fertile Neogene lowlands of north-central Crete, from Knossos eastwards to Karteros and westwards to Tylissos, share a fairly tight range of values.

Substantially higher and/or lower ratios were obtained in east-central Crete (around Mirabello) and in all the upland areas sampled. The distinctiveness from KK of upland karstic features is useful for this study, since these are the main locations for summer grazing of modern transhumant sheep flocks (Figure 5, left). It must be acknowledged that animals grazing on a range of bedrocks with contrasting (higher and lower than the KK mean) $^{87}\text{Sr}/^{86}\text{Sr}$ (for example on Psiloritis) might yield average

ratios compatible with the wider Knossian territory. On the other hand, the Mirabello coast produced $^{87}\text{Sr}/^{86}\text{Sr}$ ratios distinctly different from those of coastal central Crete, but partly overlapping with the lower values from the uplands. A combined analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and other isotopes may help resolve such ambiguities (Section 5.2.2.). With these latter notes of caution, therefore, there is potential for identifying herbivores (browsers more easily than grazers) that had spent time outside the north-central lowland core of the Knossian polity.

5.1.2. *Ligneous vs. non-ligneous plants and atmospheric strontium inputs*

Ligneous plants tend to have slightly lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than non-ligneous (mean difference=0.00018; based on 20 locations where both ligneous and non-ligneous plants were collected; Table 1). Mean annual precipitation (derived from interpolation of average monthly climate data for 1960-1990, from the WorldClim database; Hijmans et al., 2005) has a significant effect on $^{87}\text{Sr}/^{86}\text{Sr}$ of non-ligneous plants collected during mid-spring, which increase with rising precipitation ($F(1, 9)=11.85$, $p=0.007$, $R^2=0.52$), but not on those collected in late autumn 2013 at the end of a lengthy drought (with minimal rainfall between May and mid-November; Figure 6a). A similar, though weak correlation is observed in ligneous plants collected during mid-spring ($F(1, 15)=4.39$, $p=0.0537$, $R^2=0.17$), but not for those collected in late autumn (Figure 6b). These results are consistent with the expectation from previous studies that the $^{87}\text{Sr}/^{86}\text{Sr}$ of deeper-rooting ligneous plants should tend to be influenced more by bedrock and those of shallow-rooting non-ligneous plants more by atmospheric inputs (e.g. Hartman and Richards, 2014). As a result, local differences in bedrock $^{87}\text{Sr}/^{86}\text{Sr}$ are more likely to be reflected in browsing than grazing animals and thus perhaps in goats more than in sheep.

5.2. *Archaeological tooth enamel analysis*

5.2.1. $^{87}\text{Sr}/^{86}\text{Sr}$

Tables 3 and S3 and Figure 7 show the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of sheep and goat tooth enamel bioapatite samples. All individuals (with the exception of goat RR188) display low intra-tooth variation in $^{87}\text{Sr}/^{86}\text{Sr}$ (< 0.00012) and there is no statistically significant

difference in the amplitude of sheep and goat intra-tooth $^{87}\text{Sr}/^{86}\text{Sr}$ ($t(3.477)=2.521$, $p=0.0746$, M_2 s only).

Sample ID	Species	Tooth	Mean $\delta^{13}\text{C}$ (‰)	Estimated Plant $\delta^{13}\text{C}$ (‰) ^a	Min $\delta^{13}\text{C}$ (‰)	Max $\delta^{13}\text{C}$ (‰)	$\Delta^{13}\text{C}$ (‰) ^b	Mean $\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	Min $\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	Max $\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	$\Delta^{18}\text{O}$ (‰)	Mean $^{87}\text{Sr}/^{86}\text{Sr}$	$\Delta^{87}\text{Sr}/^{86}\text{Sr}$
MUM70	Goat	M2	-10.8	-25.4	-11.3	-10.3	0.9	-0.1	-2.0	2.1	4.1	0.70892	0.000083
MUM73	Goat	M2	-11.2	-25.8	-11.4	-10.9	0.5	-0.3	-2.3	0.9	3.2	0.70901	0.000087
MUM78	Goat	M2	-11.5	-26.1	-12.1	-11.0	1.1	-1.4	-3.4	0.4	3.7	0.70929	0.000088
RR188	Goat	M2	-10.8	-25.4	-11.4	-10.4	1.0	-2.1	-4.6	-0.1	4.5	0.70866	0.000233
		M3	-10.9	-25.5	-11.2	-10.6	0.7	-3.4	-5.2	-0.8	4.4	0.70839	0.000176
MUM72	Sheep	M2	-11.9	-26.5	-12.9	-10.8	2.1	-3.2	-4.0	-1.8	2.2	0.70904	0.000010
MUM75	Sheep	M2	-11.2	-25.8	-12.1	-9.9	2.1	-2.2	-3.5	-0.7	2.8	0.70903	0.000023
RR191	Sheep	M2	-10.8	-25.4	-11.6	-10.0	1.6	-2.4	-3.7	-1.3	2.4	0.70889	0.000046
		M3	-11.5	-26.1	-12.7	-9.5	3.2	-1.9	-3.0	-0.6	2.4	0.70886	0.000118

Table 3. Summary $\delta^{18}\text{O}_{\text{VPDB}}$ and $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of faunal tooth enamel bioapatite from Knossos.

^a Calculated using $\epsilon^*_{\text{enamel-diet}}$ of 14.6‰ (Passey et al. 2005, table 2).

^b Δ is amplitude of intra-tooth isotopic variation.

This could mean either that the animals did not range widely during their lifetime, or that they moved between regions with very similar bioavailable strontium. Four animals (goats MUM73 and 78 and sheep MUM72 and 75) yielded ratios within the KK range (mean= 0.7091 ± 0.0001) and goat MUM70 ratio is very close. Three goats and two sheep from MUM are thus compatible with a ‘local’ origin, although, as noted above, a more distant origin in an area of mixed geology supporting pasture plants with both higher and lower values (Section 5.1.) cannot be excluded when considering $^{87}\text{Sr}/^{86}\text{Sr}$ in isolation. Goat RR188 has the lowest and most distinct ratios, outside the KK range and overlapping with low upland and Mirabello. It also displays the greatest intra- and inter-tooth variation (>0.00018), perhaps indicating relocation during its lifespan (based on tooth eruption and wear, it was slaughtered 2-3 years after birth). Sheep RR191 ratios are also slightly lower than the KK range. These two specimens (perhaps significantly, both from the same – Royal Road – context at Knossos) are the most likely candidates for having been raised in regions with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios distinct from KK. Section 5.2.2 explores how $\delta^{18}\text{O}$ analysis may help choose between the different options.

5.2.2. $\delta^{18}\text{O}$ values

Tables 3 and S3 and Figures 7-8 show the $\delta^{18}\text{O}$ values of sequential tooth enamel bioapatite samples. The sequence of samples for each tooth apparently represents much of an annual cycle: logically, the first year of life, in the case of M_2 , and the second, in the case of M_3 . In the case of goat RR188 and sheep RR191, M_2 and M_3 together represent much of two annual cycles.

$\delta^{18}\text{O}$ values range from -4.0 to -0.6‰ in sheep, and from -5.2 to 2.1‰ in goats. Although there is no significant difference in the minimum values between the two species ($t(3.41)=1.0$, $p=0.363$), the maximum, mean and amplitude of intra-tooth variation are all significantly lower in sheep than goat M_2 s ($p<0.05$; Table 4; Figure 9). The lower amplitude of sheep enamel $\delta^{18}\text{O}$ values is the opposite of what would be expected of animals grazing shallow-rooted annuals, which should vary more with seasonal precipitation and temperature than deep-rooted (lignaceous) browse (bushes and trees).

Group 1	Group 2	Isotopic data	Parameter	t	df	p ^a
Goats	Sheep	$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	mean	2.85	4.84	0.037
			min	1.00	3.41	0.363
			max	3.64	4.85	0.016
			amplitude	4.28	4.63	0.009
		$\delta^{13}\text{C}$ (‰)	mean	0.55	3.11	0.618
			min	1.42	2.93	0.253
			max	-1.15	3.45	0.322
			amplitude	-4.67	3.95	0.010

Table 4. Results of two-way significance t-tests of mean, minimum, maximum and amplitude of $\delta^{18}\text{O}_{\text{VPDB}}$ and $\delta^{13}\text{C}$ values of sheep and goat tooth enamel bioapatite.

^a P values < 0.05 shown in bold.

The absence of meaningful difference between sheep and goat $\delta^{18}\text{O}$ minimum values in combination with the differing amplitude patterns is most parsimoniously interpreted as follows. The high amplitude-high maximum $\delta^{18}\text{O}$ values in goats are more compatible with contrasting seasonal climates in a single location, probably lowland rather than upland given the lack of a significant difference between the two species' minimum $\delta^{18}\text{O}$ values. Conversely, low amplitude-attenuated maximum $\delta^{18}\text{O}$ values in sheep are more compatible with dampened inter-seasonal climatic variation and so with removal of animals in the warmer months to the uplands. Here cooler and

wetter conditions, coupled with the documented decrease in $\delta^{18}\text{O}$ values of precipitation with increasing elevation, will have resulted in lower $\delta^{18}\text{O}$ values than prevailed in the lowlands during the hot/dry season. This ‘dampened’ seasonality is observed mostly in sheep (Table 4; Figure 8) and is suggestive of greater vertical mobility for sheep compared to goats (cf. Dansgaard, 1964).

These $\delta^{18}\text{O}$ data represent the first direct evidence that at least some FP sheep in central Crete did move seasonally between lowland winter grazing (perhaps stubble and fallow fields, judging by the recorded ‘location’ of flocks) and upland summer pastures. This insight has significant potential implications for understanding not only animal management, but also palatial political economy, in FP Crete.

The ‘exotic’ goat RR188 displays the lowest minimum $\delta^{18}\text{O}$ value of any of the teeth sampled, as well as the most distinct and variable $^{87}\text{Sr}/^{86}\text{Sr}$ values, compatible with modern upland karstic and lowland Mirabello plant values. In combination, its $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values (Section 5.2.1) suggest a provenance away from KK, and in a region experiencing cooler/wetter winters than those where the other animals were pastured, thus ruling out hot and arid eastern Crete and instead suggesting either a mid-altitude central Cretan location or western Crete as possible sources. The latter area is thought to be the probable source of a few livestock (cattle) listed as sent to Knossos on Linear B text C(1) 5753 (Godart 1971).

5.2.3. $\delta^{13}\text{C}$ values

Tables 3 and S3 and Figure 8 show $\delta^{13}\text{C}$ values of sequential tooth enamel bioapatite samples. The $\delta^{13}\text{C}$ values of sheep and goats exhibit no significant differences in minimum, maximum or mean, but the amplitude of intra-tooth variation is significantly greater ($t(3.95)=-4.67$, $p=0.010$) in sheep (-12.9 to -9.5‰) than goat (-12.1 to -10.3‰) $\text{M}_{2\text{S}}$ (Table 4; Figure 10).

Sheep and goat *diet* $\delta^{13}\text{C}$ values, calculated by subtracting from tooth enamel $\delta^{13}\text{C}$ values the 14.6‰ offset suggested by Passey et al. (2005, table 2) for cattle, are consistent with overwhelming consumption of plants with a C_3 photosynthetic pathway (mean = -25.7‰ $\pm$ 0.39, Table 3). Values are largely compatible with measured values of roughly contemporary cereal, pulse and tree crops. Slightly earlier

(LM II) food storage contexts at Knossos provided average values of -24.5‰ for cereal and -23‰ for pulse grains respectively (Nitsch et al., in press). Charred olive and *Quercus ilex* type remains, both likely to have grown in open conditions, from 3rd and 2nd mill. BC Ebla and Qatna in the east Mediterranean yielded $\delta^{13}\text{C}$ values of -23.9‰ (olive stone average), -24.9‰ (olive wood) and -22.3‰ (*Quercus ilex* type wood) (Fiorentino et al., 2012, table 2). They are also compatible with modern plant values from Israel, growing under similar climatic conditions (average -26.5‰; Hartman and Danin, 2010, table 1, fig. 4), even when these are corrected for the shift between present and prehistoric atmospheric $\delta^{13}\text{C}$ (ca. 2‰; cf. Drucker et al., 2008; Francey et al., 2005). Values at the higher end of the range are likely to result from feeding on plants growing mainly in open and/or saline (coastal) conditions, both compatible with Cretan floral communities exploited today by sheep and goats (Section 3.3).

$\delta^{13}\text{C}$ values tend to be lower for sheep than for goat, implying that the two species exercised their preferences for grazing and browsing, respectively, and so that goats at least ranged largely on uncultivated pasture (Figure 5, right), whereas sheep could in theory have maintained a grazing habit on cultivated land. If both species overwintered in the lowlands, as inferred from the $\delta^{18}\text{O}$ data, and if sheep exercised their preference for grazing while goats tended to browse, then the lower $\delta^{13}\text{C}$ minima observed in sheep would be expected. Conversely, again following the $\delta^{18}\text{O}$ data, if in summer sheep moved to much higher pasture and goats not, then increases in sheep $\delta^{13}\text{C}$ values resulting from greater altitude would offset and perhaps exceed their reduction as a result of grazing rather than browsing. In addition, on the high pastures, sheep would have grazed vegetation that had not grown (because of low winter temperatures, a longer rainy season and often late snow melt) until late spring-early summer, when temperatures are higher, and so would presumably have had elevated $\delta^{13}\text{C}$ values. The $\delta^{13}\text{C}$ data therefore are compatible with a contrast between grazing sheep moving between winter pastures in the lowlands and summer pastures in the uplands, while browsing goats were relatively restricted in mobility.

5.2.3. Insights from multi-isotope synthesis

647 Integration of these data with the $\delta^{18}\text{O}$ evidence for seasonality, however, suggests a
 648 more complex picture. The $\delta^{13}\text{C}$ values rise and fall *in tandem* with $\delta^{18}\text{O}$ values in the
 649 case of goats MUM70 and MUM78, consistent with feeding on seasonally available
 650 vegetation, and *over part of the sequence* in the case of two out of three sheep
 651 (MUM75 and RR191), consistent with expected seasonal variation in winter lowland
 652 versus summer upland graze (below). The relationship between the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$
 653 curves is unambiguously *not* as expected, however, for the two remaining goats,
 654 MUM73 and RR188, in which $\delta^{13}\text{C}$ values seem insensitive to the changing seasons,
 655 and for the one remaining sheep (MUM72), in which $\delta^{13}\text{C}$ rises when $\delta^{18}\text{O}$ falls and
 656 *vice versa*. The $\delta^{13}\text{C}$ values of goats MUM73 and RR188, as well as insensitive to
 657 seasonality, are relatively high in comparison to the other examples (Figure 8),
 658 suggesting that these individuals consumed an atypically high- $\delta^{13}\text{C}$ diet in winter (e.g.
 659 stored fodder harvested in summer or rough coastal pasture rich in C_4 /halophyte
 660 plants) or atypically low- $\delta^{13}\text{C}$ diet in summer (e.g. stored fodder harvested in winter).
 661 Of these three hypothetical scenarios, the first is certainly viable: the known $\delta^{13}\text{C}$
 662 values of slightly earlier LMII cereals and pulses from Knossos are equivalent to
 663 tooth enamel values of -10.4‰ and -8.9‰ (Section 3.3), so a diet rich in stored grain
 664 would comfortably raise winter values to summer levels – as would less generous
 665 rations of C_4 *Cyperus*. The feasibility of the second scenario (grazing on rough coastal
 666 pasture) is less clear and its evaluation would require survey of the floristic
 667 composition of modern coastal rough pasture in winter and of the extent to which
 668 sheep and goats herded on this select halophytes and C_4 plants. The ethnography of
 669 recent animal husbandry suggests that the third scenario, consumption in summer of
 670 fodder collected and stored in the cool and wet half of the year, is much less likely
 671 than the first, but does offer at least one possible context for such a practice. In a mild
 672 and wet spring, cereals sown on fertile (especially manured) ground may grow too
 673 vigorously, leading to ‘lodging’ (stem collapse) and/or excessive weed infestation,
 674 and as a result may be cut early and dried as hay. Such measures for extracting some
 675 benefit from failed crops were relatively commonplace in the recent past in northern
 676 Greece (Halstead, 2014, 193-9), although excessive growth is a less likely problem
 677 (and heavy manuring more likely to have been avoided) in the more arid climate of
 678 central Crete (Halstead, field notes).

Foddering is at least compatible with Linear B references to finished animals. Although the texts do not specify how this was achieved, plausible options, discussed above, include feeding livestock on crop residues or surplus grain from the C₃ cereals and pulses attested archaeobotanically or perhaps on a C₄ *Cyperus* species. If fodder, whatever its composition, was used to ‘finish’ animals, however, this should have taken place in the last weeks or months before slaughter and so should be reflected (if at all, given delays in mineralisation) in the most recently formed enamel, located closest to the base of the tooth, as is the case with the ‘aberrant’ sheep MUM72. In the case of aberrant goats MUM73 and RR188, however, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves diverge at both the beginning and the end of the sequence of incremental values, so if the divergent $\delta^{13}\text{C}$ values are the result of foddering, then this did not take place in the context of finishing for slaughter as described in Linear B.

Sheep MUM75 and RR191 exhibit partial matches between the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves, with partial divergence conceivably attributable to these animals having moved upwards in spring or downwards in autumn unseasonally early or late; this often happened in the recent past, either because the date of onset of summer or winter weather was variable, or because herders were constrained by scheduling conflicts with other activities or by the availability of pasture at their destination (Halstead and Isaakidou, fieldnotes). Such mismatch is well documented in the recent past, most dramatically in the occasional burial of flocks by unexpectedly early or late snowfall in the mountains (e.g. Halstead and Isaakidou, field notes; Mavrakakis, 1948, 74-6).

In sheep MUM72 a more consistent pattern of inversely correlated $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values can be observed. Again it is possible that winter values were raised by grazing on coastal rough pasture or by consumption of fodder harvested in summer and, perhaps less plausibly, that summer values were depressed by rations of fodder harvested in winter or early spring, but to hypothesise an ‘out-of-season’ diet in both winter and summer demands considerable special pleading. It is the $\delta^{13}\text{C}$ rather than $\delta^{18}\text{O}$ values that are unexpected, since on Crete both temperature and precipitation are variable from year to year, but summers, even in the mountains are not cooler and wetter than winters in the lowlands (Figure 2). In the case of the Knossos sheep MUM72, understanding of the ‘mismatch’ between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values must await further actualistic investigation of modern plants and herbivores on Crete. Inversions

of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ patterns, observed in previous studies, have largely been attributed to vertical translocation of animals, but in wet summer/dry winter climatic regimes (e.g. Makarewicz and Pederzani, 2017; Tornero et al., 2016) very different to that prevalent in Crete and thus inappropriate for understanding the present dataset.

Finally, given the Linear B indications of subdivision of sheep and goats by age and sex, some differences of diet and mobility, and hence $\delta^{13}\text{C}$ values, between individual animals would not be surprising. No consistent contrasts were observed, however, between sheep MUM72 and goat MUM78, slaughtered below two years of age, and the remaining animals, killed slightly older in their third year.

7. Conclusion

The problems tackled by this study are partly historical and partly methodological. As regards the former, analysis of $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the tooth enamel of four goats and three sheep has indeed unlocked several aspects of their life histories, including long-term horizontal displacement, seasonal vertical mobility, and overall feeding strategy (browsing versus grazing), as well as more enigmatic indications of dietary variability that implies distinctive foddering or pasturing trajectories for some of these animals.

These life-history details shed significant new light on animal management in Final Palatial Crete and, by extension, on palatial political economy, although potential insights are limited at this stage by four factors. First, of course, the sample size is too small for safe extrapolation to the whole of the Knossian polity or even to Knossos itself, as the apparent contrast in $^{87}\text{Sr}/^{86}\text{Sr}$ values from MUM and the Royal Road highlights. Secondly, given the selective coverage of Linear B records, it is unknown whether the animals sampled at Knossos were drawn from the spheres of animal husbandry monitored by palatial administrators or from the ‘non-palatial’ sector. To clarify this issue will require not only larger samples from Knossos but also analysis of animal teeth from sites of varying status spread across and beyond the Knossian polity. Thirdly, these tooth samples of necessity shed light only on the period of enamel formation, that is for sheep and goats the first (M_2) and second (M_3) years of life, and are taken from animals slaughtered in their second or third year which roughly represents the transition to productive adulthood. By virtue of their young age

of slaughter, these animals are ostensibly atypical of most of the livestock listed in Linear B and the period of life covered by their incremental tooth enamel samples is largely ignored by the texts. To address this problem, it will be necessary to diverge from earlier practice and sample teeth of animals slaughtered at an older age. The fourth factor to be considered is methodological. This pilot study has amply demonstrated the benefits of the multi-isotope approach adopted here, with $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values providing complementary insights in both isolation and combination. Nonetheless, the need for more actualistic work on modern plants and animals of known ecological context and life history is abundantly clear and is essential in particular to enable reliable understanding of variation in animal movement and diet beyond the broad-brush distinction between browsing goats that undertook little vertical movement and grazing sheep that alternated seasonally between lowlands and uplands. Beyond these more general trends, and despite the small scale of these first analyses, variation in movement and diet is already apparent. Some of this variation is doubtless due to the geographical heterogeneity of the Knossian polity and to inter-annual variability in weather, but diversity of practice may also have been more characteristic of smaller-scale ‘non-palatial’ than of large-scale, centrally administered animal husbandry. Understanding of variation in movement and diet may thus provide a window onto the resource flows between the palatial and non-palatial sectors that are seen, for the most part, only very indirectly in the Linear B record.

To this end, obvious priorities for future actualistic research include: (i) better definition of variation in bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ values by further systematic sampling of modern plants in more diverse topographic and geological settings; (ii) determination of intra-tooth variation in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in modern animals undertaking vertical transhumance and in others moving only locally; (iii) investigation of the effect of winter foddering with summer-collected plants and of summer foddering with spring-collected plants on intra-tooth $\delta^{13}\text{C}$ values; (iv) establishment of the range of $\delta^{13}\text{C}$ values of natural (uncultivated) vegetation in plant communities (e.g. coastal, ruderal) that were traditionally important as rough pasture.

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Figure 1. Simplified geological map of Crete (A) and insets (B-D) with detailed geological formations, modern plant collection localities (cf. Table 1) and archaeological sites and regions mentioned in the text (general map after Kneucker et al., 2015; Papanikolaou and Vassilakis, 2010; Zulauf et al., 2016; inset B: IGME geological map, Herakleio Sheet 1996; inset C: IGME Epano Archanes Sheet 1994; IGME Tymbaki Sheet 1984; Siart et al., 2010; inset D: IGME Mochos Sheet 1989; IGME Agios Nikolaos Sheet 1987).

Figure 2. 2010-2017 average monthly temperature and precipitation from stations closest to areas relevant to present study (data source: National Observatory of Athens records, <http://meteosearch.meteo.gr/>; see Supplementary Table S1 for data used); (key:

Figure 3. Sheep grazing on the rocky coastline north-east of Palaikastro (eastern Crete, July 2015).

Figure 5. Left: sheep grazing endemic 'nevrida' (*Polygonum idaeum*) on the Nida polje (November 2013). Right: goats browsing evergreen oak on surrounding slopes (September 2005).

Figure 6. Effect of mean annual precipitation on $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of: a) non-ligneous plants and b) ligneous plants (precipitation data from the WorldClim database).

Figure 7. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (black symbols) and $\delta^{18}\text{O}$ (open symbols) of sheep and goat tooth enamel bioapatite from Knossos (ERJ = enamel-root junction).

Figure 8. $\delta^{18}\text{OVPDB}$ (open symbols) and $\delta^{13}\text{C}$ values (black symbols) of sheep and goat tooth enamel bioapatite from Knossos (ERJ = enamel-root junction).

Figure 9. Average $\delta^{18}\text{O}_{\text{VPDB}}$ values and standard deviations of sampled archaeological teeth from Knossos (solid: goat; open: sheep; second mandibular molars [M_2], unless otherwise indicated).

Figure 10. Average $\delta^{13}\text{C}$ values and standard deviations of sampled archaeological teeth from Knossos (solid: goat; open: sheep; second mandibular molars [M_2], unless otherwise indicated).

Area	Fig. 1 Locality Code	Elevation (masl)	Mean annual precipitation (mm)*	Geology	Geological Age	Source for geological date	Latitude	Longitude	Sample ID	Plant species (ligneous)	Ligneous *Sr ⁸⁷ / ⁸⁶ Sr	Sample ID	Plant species (non-ligneous)	Non ligneous *Sr ⁸⁷ / ⁸⁶ Sr	Season of collection
Knossos - Kairatos banks	1	70	652	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene	IGME ^b Herakleio Sheet 1996	35.299551	25.165527	1a	Carob tree (<i>Ceratonia siliqua</i>)	0.708922	—	—	—	Dry
	2	66	652	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.298720	25.165445	2a	Plane tree (<i>Platanus orientalis</i>)	0.708923	—	—	—	Dry
							35.298717	25.165760	2b	Walnut tree (<i>Juglans juglans</i>)	0.708939	—	—	—	Dry
Knossos-Allias	3	141	652	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene	IGME Herakleio Sheet 1996	35.298494	25.168850	3a	Fig tree (<i>Ficus carica</i>)	0.709149	—	—	—	Dry
	4	143	652	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.297756	25.169154	4a	Sage (<i>Salvia cf. fruticosa</i>)	0.709392	—	—	—	Dry
	5	169	652	Calcareous marls, marly limestones (Ag. Varvara Formation)	Upper Miocene		35.296440	25.169280	5a	Wild olive (<i>Olea europaea ?oleaster</i>)	0.709253	5b	<i>Dasypprium villosum</i>	0.709094	Wet
Knossos- Gypsades	6	160	589	Gypsums (Ag. Varvara Formation)	Upper Miocene	IGME Herakleio Sheet 1996	35.285540	25.155800	6a	Almond tree (<i>Prunus dulcis</i>)	0.708959	6c	Herbaceous compositae	0.709126	Wet
Karteros Valley	7	1	507	alluvium	Quaternary	IGME Herakleio Sheet 1996	35.333120	25.192180	6b	<i>Eberus cretica</i>	0.709042	7a	Oat	0.709317	Dry
	8	9	507	Calcareous marls, marly limestones (Ag. Varvara Formation)	Upper Miocene		35.332620	25.190765	8a	Poplar tree (<i>Populus</i> spp.)	0.709064	—	—	—	Dry
									8b	Small poplar (ground)	0.708919	—	—	—	Dry
	9	3	508	alluvium	Quaternary		35.331367	25.203805	9a	Fig tree (<i>Ficus carica</i>)	0.70925	—	—	—	Dry
	10	1	507	alluvium	Quaternary		35.330070	25.193860	10a	Poplar tree (<i>Populus</i> spp.)	0.709021	10b	<i>Dasypprium villosum</i>	0.709124	Dry
	11	4	542	alluvium	Quaternary		35.319510	25.199230	11a	Plane tree (<i>Platanus orientalis</i>)	0.709005	11b	<i>Dasypprium villosum</i>	0.709152	Dry
	12	12	543	alluvium	Quaternary		35.314470	25.199060	12a	Fig tree (<i>Ficus carica</i>)	0.709094	12b	Oat	0.709179	Dry
	13	17	543	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.311230	25.201720	13a	Olive tree (<i>Olea europaea</i>)	0.709363	—	—	—	Dry
									13b	Sage (<i>Salvia cf. fruticosa</i>)	0.70919	—	—	—	Dry
	14	26	532	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.302880	25.202360	14a	Plane tree (<i>Platanus orientalis</i>)	0.709005	14b	Stachys	0.709037	Dry
	15	82	532	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.302215	25.206463	15a	Almond tree (<i>Prunus dulcis</i>)	0.70914	—	—	—	Dry
	16	76	548	Calcareous marls, marly limestones (Ag. Varvara Formation)	Upper Miocene		35.302215	25.207100	15b	<i>Pistacia terebinthus</i>	0.709217	—	—	—	Dry
Juktas - East facing slopes	17	85	596	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene	IGME Epano Archanes Sheet 1994	35.278158	25.204962	16a	Almond tree (<i>Prunus dulcis</i>)	0.709051	16b	Thyme (<i>Thymus</i> spp.)	0.709112	Dry
	18	221	667	Marls, limestones, marl breccias (Finikia Formation)	Lower-Middle Pliocene		35.233512	25.221590	17a	Plane tree (<i>Platanus orientalis</i>)	0.709034	17b	<i>Verbascum</i> spp.	0.709179	Dry
									18a	Walnut tree (<i>Juglans juglans</i>)	0.708986	—	—	—	Dry
									18b	Caper (<i>Capparis spinosa</i>)	0.709094	—	—	—	Dry
	19	779	886	Limestone (Tripolis Unit)	Upper Cretaceous		35.240160	25.144590	19a	<i>Quercus coccifera</i> /lex	0.709138	19b	Herbaceous compositae	0.709092	Wet
	20	748	886	Limestone (Tripolis Unit)	Upper Cretaceous		35.234530	25.142180	20a	<i>Quercus coccifera</i> /lex	0.709203	—	—	—	Wet
									20b	Sage (<i>Salvia cf. fruticosa</i>)	0.709091	—	—	—	Wet
Aghios Georgios Epanosphi Monastery	21	533	814	Ophiolites (Uppermost Unit)	Lower Miocene (tectonic emplacement); Upper Jurassic-Cretaceous (K-Ar dates)	Koepeke et al. 2002, table 4	35.152430	25.136230	21a	<i>Phlomis</i> sp.	0.709711	21c	Herbaceous compositae	0.709623	Wet
							35.148240	25.138320	21b	Wild pear (<i>Pyrus spinosa</i>)	0.710232	—	—	—	Wet
Tylissos	22	221	683	Calcareous marls, marly limestones (Ag. Varvara Formation)	Upper Miocene	IGME Herakleio Sheet 1996	35.298270	25.008030	22a	<i>Pistacia terebinthus</i>	0.709115	22b	<i>Hordeum bulbosum</i>	0.709349	Dry
Psiloritis - Karstic feature west of Embriskos	23	1400	1016	alluvium/	Quaternary	IGME Map Tyrbaki Sheet 1984; Siart et al., 2010	35.218073	24.865700	23a	Walnut tree (<i>Juglans juglans</i>)	0.708302	—	—	—	Dry
Nida polje	24	1344	1014	alluvium/	Quaternary	IGME Map Tyrbaki Sheet 1984	35.205348	24.841267	23b	Fruit tree (<i>Malus</i> spp.)	0.708587	—	—	—	Dry
Psiloritis - Slopes overlooking Nida from south-west	25	1415	1014	Platy limestones (Plattenkalk Unit)	Permian - Upper Oligocene- Lower Miocene ^d		35.184277	24.838384	25a	Field maple (<i>Acer sarpentines</i>)	0.708664	25b	<i>Euphorbia acanthothamnus</i>	0.708305	Dry
	26	1341	1013	Platy limestones (Plattenkalk Unit)	Permian - Upper Oligocene- Lower Miocene ^d		35.184022	24.838039	—	—	—	25c	Herbaceous perennial	0.70948	Dry
Psiloritis - Hill to south-east of Zomithos	27	1249	1014	Limestones/dolomitic limestones/dolomites (Tripolis unit)	Upper Jurassic	IGME Map Tyrbaki Sheet 1984	35.174171	24.843016	26a	Oak (<i>Quercus ?ilex</i>)	0.708673	—	—	—	Dry
							35.244120	24.893420	27a	<i>Quercus coccifera</i>	0.709609	27b	Herbaceous perennial	0.71043	Wet
Lasithi-Plati	28	868	854	Phyllites-quartzites-shales (Phyllite- Quartzite Unit)	Upper Carboniferous-Lower Triassic (sedimentation) (Upper Oligocene-Lower Miocene HP/LT metamorphism ^f)	Krahl et al., 1983; Oliva-Urcia et al., 2010	35.168580	25.438110	28a	—	0.709623	28b	Herbaceous compositae	0.709676	Wet
Lasithi-Pinakiano	29	826	836	Limestones/dolomitic limestones/dolomites (Tripolis Unit)	Upper Triassic - Upper Jurassic	IGME Mochos Sheet 1989; Krahl et al., 1983	35.196960	25.463090	29a	<i>Quercus coccifera</i>	0.709064	29b	Herbaceous perennial	0.714506 ^g	Wet
Lasithi-Aghios Georgios	30	817	836	alluvium/	Quaternary		35.196670	25.462830	30a	Apple/pear tree	0.708678	30b	Cruciferae	0.70876	Wet
	31	832	831	alluvium/	Quaternary		35.168280	25.489940	31a	Fruit tree (apple/pear/plum)	0.708293	31c	Herbaceous perennial	0.708259	Wet
Lasithi-Aghios Konstantinos									31b	Apple/pear tree	0.70842	—	—	—	Wet
	32	837	830	alluvium/	Quaternary	Krahl et al., 1983; Oliva-Urcia et al., 2010	35.177760	25.502640	32a	Hawthorn (<i>Crataegus</i> sp.)	0.708554	32b	Herbaceous perennial	0.708691	Wet
	33	841	830	Phyllites-quartzites-shales (Phyllite- Quartzite Unit)	Upper Carboniferous-Lower Triassic (sedimentation) (Upper Oligocene-Lower Miocene HP/LT metamorphism ^f)		35.179220	25.504920	33a	Apple/pear tree	0.709673	33b	Herbaceous perennial	0.709586	Wet
Katharo	34	1130	888	Limestones/dolomitic limestones/dolomites (Tripolis Unit)	Upper Triassic - Upper Jurassic	IGME Ag. Nikolaos Sheet 1987	35.156250	25.537718	34a	Field maple (<i>Acer sarpentines</i>)	0.707805	—	—	—	Dry
									34b	<i>Phlomis</i> sp.	0.70845	—	—	—	Dry
Mirabello - Kalos Potamos stream north-west of Kalo Chorio	35	15	501	alluvium	Quaternary	IGME Ag. Nikolaos Sheet 1987	35.120420	25.723640	35a	Plane tree (<i>Platanus orientalis</i>)	0.707986	35b	Oat	0.708231	Wet
Mirabello - Alendis Christos	36	109	525	Limestone breccias/Granites- Granodiorites (Uppermost Unit)	neogene (mesones) - Miocene/Eocene (crystallisation of igneous rocks) - Granodiorites = <i>Lower Carboniferous-Lower</i>	IGME Ag. Nik. Sheet 1987; Langosch et al., 2000; Kneucker et al., 2015	35.112010	25.732234	36a	<i>Pistacia terebinthus</i>	0.708389	36b	Oat	0.708321	Wet

Table 1. List of collected modern plants.

* Data from WorldClim database.

^b IGME = Institute of Geological and Mineralogical Exploration.

^d Aberrant values excluded from discussion.

Supplementary Tables

Monthly averages 2010-2017		January	February	March	April	May	June	July	August	September	October	November	December
Tzermiado – Lasithi Plateau (820 masl)													
Temperature (°C)		6.0	7.3	8.5	11.5	15.2	18.5	19.8	19.8	17.7	13.7	10.7	7.2
Precipitation (mm)		235.9	144.7	99.1	53.3	48.9	10.2	15.3	4.9	26.6	96.4	83.9	213.4
Anogeia-Psiloritis (800 masl)													
Temperature		6.9	8.1	9.7	13.2	17.1	20.8	22.8	22.6	20.3	15.5	12.2	8.3
Precipitation		221.8	147.5	98.5	38.9	39.7	6.7	1.4	2.7	32.3	124.3	85.7	197.6
Herakleio South (115 masl)													
Temperature		12.3	13.2	14.3	17.2	20.7	24.3	26.7	26.6	24.3	20.4	17.2	13.7
Precipitation		113.8	62.0	50.0	17.6	15.5	2.1	0.1	3.6	15.0	57.4	45.8	106.3

Supplementary Table S1. Data for Figure 2 (data from records of the National Observatory of Athens, <http://meteosearch.meteo.gr/>).

Sample ID	Tooth	Leaching step	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
MUM73	M2	un-leached	0.70903	0.000013
		1	0.70901	0.000014
		5	0.70900	0.000010
		10	0.70900	0.000011
		15	0.70903	0.000013
		20	0.70903	0.000011
RR191	M2	un-leached	0.70895	0.000011

1	0.70888	0.000020
5	0.70892	0.000010
10	0.70896	0.000012
15	0.70901	0.000013
20	Sr concentration too low	n/a

Supplementary Table S2. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of leachates successively removed from enamel leached in buffered acetic acid.

Sample ID ^a	Species	Tooth	Payne Stage ^c	Distance from erj ^b (mm)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
MUM70 M2-1	goat	M2	E (2-3 years)	28.2	-11.1	-1.5	0.708899	0.000010
MUM70 M2-2				27				
MUM70 M2-3				26.1	-11.3	-1.0		
MUM70 M2-4				24.1				
MUM70 M2-5				22.7	-11.1	-0.1		
MUM70 M2-6				21.2			0.708896	0.000011
MUM70 M2-7				19.4	-10.9	1.3		
MUM70 M2-8				18.1				
MUM70 M2-9				16.6	-10.6	2.1		
MUM70 M2-10				14.9				
MUM70 M2-11				13.4	-10.3	1.5		
MUM70 M2-12				12.9				

MUM70 M2-13				10.5	-10.5	0.7		
MUM70 M2-14				9.2				
MUM70 M2-15				6.7	-10.7	-1.8		
MUM70 M2-16				5.4				
MUM70 M2-17				3.6	-11.0	-2.0	0.708979	0.000011
MUM70 M2-18				1.3				
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MUM73 M2-1	goat	M2	E (2-3 years)	29.6	-10.9	-2.3	0.708958	0.000012
MUM73 M2-2				27.9				
MUM73 M2-3				26.4	-11.1	-1.4		
MUM73 M2-4				24.8				
MUM73 M2-5				23.2	-11.0	-0.7		
MUM73 M2-6				21.7				
MUM73 M2-7				20.4	-10.9	0.2		
MUM73 M2-8				19.4				
MUM73 M2-9				18.2	-10.9	0.1		
MUM73 M2-10				17.1				
MUM73 M2-11				15.8	-11.2	0.3		
MUM73 M2-12				14.6				
MUM73 M2-13				13.5	-11.4	0.9	0.709021	0.000012
MUM73 M2-14				11.9				
MUM73 M2-15				10.8	-11.3	0.8		
MUM73 M2-16				9.6				
MUM73 M2-17				8	-11.4	0.0		
MUM73 M2-18				6.8				
MUM73 M2-19				5.7	-11.4	-0.7	0.709045	0.000012
MUM73 M2-20				4.1				

MUM78 M2-1	goat	M2	D (1-2 yrs)	30.4	-11.4	-3.4	0.709329	0.000009
MUM78 M2-2				29.1				
MUM78 M2-3				27.8	-11.6	-3.3		
MUM78 M2-4				26.2				
MUM78 M2-5				24.8	-12.0	-3.3		
MUM78 M2-6				23.6				
MUM78 M2-7				22.1	-12.1	-2.5	0.709293	0.000014
MUM78 M2-8				20.9				
MUM78 M2-9				19.6	-12.1	-1.7		
MUM78 M2-10				18.3				
MUM78 M2-11				17.1	-11.6	-0.8		
MUM78 M2-12				16.1				
MUM78 M2-13				15	-11.0	-0.3		
MUM78 M2-14				14				
MUM78 M2-15				12.8	-11.2	0.4		
MUM78 M2-16				11.1				
MUM78 M2-17				10.1	-11.1	0.3		
MUM78 M2-18				8.8				
MUM78 M2-19				7.3	-11.2	-0.2		
MUM78 M2-20				5.7				
MUM78 M2-21				4.5	-11.4	-1.0		
MUM78 M2-22				2.7				
RR188 M2-1	goat	M2	E (2-3 years)	27.9	-11.4	-3.5	0.708773	0.000012
RR188 M2-2				26.8				
RR188 M2-3				25.2	-11.1	-2.7		
RR188 M2-4				23.7				

RR188 M2-5		22.5	-11.0	-1.5		
RR188 M2-6		21.1				
RR188 M2-7		19.6	-10.9	-0.7		
RR188 M2-8		18.5				
RR188 M2-9		17	-10.7	-0.1	0.708671	0.000012
RR188 M2-10		15.8				
RR188 M2-11		14.4	-10.8	-0.3		
RR188 M2-12		13				
RR188 M2-13		11.7	-10.6	-1.0		
RR188 M2-14		10.2				
RR188 M2-15		8.8	-10.6	-2.2		
RR188 M2-16		7.2				
RR188 M2-17		6.5	-10.4	-4.4	0.70854	0.000010
RR188 M2-18		3.9	-10.6	-4.6		
RR188 M3-1	M3	33.3				
RR188 M3-2		31.7				
RR188 M3-3		30	-10.6	-4.3		
RR188 M3-4		28.6				
RR188 M3-5		27.3	-11.0	-4.8		
RR188 M3-6		26.1				
RR188 M3-7		24.7	-10.8	-4.7		
RR188 M3-8		23.5			0.708298	0.000011
RR188 M3-9		22.1	-11.2	-4.6		
RR188 M3-10		21				
RR188 M3-11		19.8	-11.2	-3.6		
RR188 M3-12		18.5				
RR188 M3-13		17.5	-11.2	-2.6	0.708407	0.000012

RR188 M3-14				16				
RR188 M3-15				14.8	-11.1	-1.0		
RR188 M3-16				13.3				
RR188 M3-17				12	-10.9	-0.8		
RR188 M3-18				10.6				
RR188 M3-19				9.1	-10.8	-1.8		
RR188 M3-20				7.4				
RR188 M3-21				5.9	-10.7	-3.8		
RR188 M3-22				4.4			0.708474	0.000011
RR188 M3-23				2.7	-10.8	-5.2		
MUM72 M2-1	sheep	M2	D (1-2 yrs)	22.7	-11.5	-3.3		
MUM72 M2-2				21.2				
MUM72 M2-3				19.3	-11.1	-3.8		
MUM72 M2-4				17.3				
MUM72 M2-5				15.8	-10.8	-4.0	0.709049	0.000010
MUM72 M2-6				14.3				
MUM72 M2-7				12.9	-11.3	-3.9		
MUM72 M2-8				11.7				
MUM72 M2-9				10.5	-12.1	-3.8	0.709046	0.000012
MUM72 M2-10				8.9				
MUM72 M2-11				7.5	-12.5	-3.1		
MUM72 M2-12				6				
MUM72 M2-13				4.3	-12.9	-2.2	0.709039	0.000012
MUM72 M2-14				2.7	-12.6	-1.8		
MUM75 M2-1	sheep	M2	E (2-3 years)	30.9	-11.1	-2.9		
MUM75 M2-2				29.5				

MUM75 M2-3				28.1	-11.7	-2.8		
MUM75 M2-4				26.8				
MUM75 M2-5				25.5	-12.0	-2.6		
MUM75 M2-6				24.6				
MUM75 M2-7				22.9	-12.1	-2.6	0.709017	0.000009
MUM75 M2-8				22				
MUM75 M2-9				20.8	-12.1	-2.2		
MUM75 M2-10				19.6				
MUM75 M2-11				18	-11.6	-1.2		
MUM75 M2-12				16.8				
MUM75 M2-13				15.8	-10.8	-0.7	0.70904	0.000008
MUM75 M2-14				14.1				
MUM75 M2-15				12.1	-10.3	-1.0		
MUM75 M2-16				10.2				
MUM75 M2-17				8.6	-9.9	-2.5		
MUM75 M2-18				7.1				
MUM75 M2-19				5.3	-10.1	-3.5	0.709026	0.000010
MUM75 M2-20				3				
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RR191 M2-1	sheep	RR191	E (2-3	26.2	-10.0	-3.7	0.708899	0.000010
RR191 M2-2		M2	years)	24.3				
RR191 M2-3				22.9	-11.0	-3.4		
RR191 M2-4				21.5				
RR191 M2-5				20.1	-11.6	-3.2		
RR191 M2-6				18.6				
RR191 M2-7				17	-11.4	-2.0		
RR191 M2-8				15.5				

RR191 M2-9			14.1	-10.9	-1.7		
RR191 M2-10			12.9				
RR191 M2-11			11.8	-10.4	-1.4		
RR191 M2-12			11			0.708915	0.000013
RR191 M2-13			9.8	-10.2	-1.3		
RR191 M2-14			8.2				
RR191 M2-15			7.1				
RR191 M2-16			5.8				
RR191 M2-17			4.5	-10.6	-2.7		
RR191 M2-18			3			0.708869	0.000012
RR191 M2-19			2	-11.0	-2.3		
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RR191 M3-1	sheep	RR191 M3	31.9				
RR191 M3-2			30.9			0.708913	0.000011
RR191 M3-3			29.6	-10.8	-2.9		
RR191 M3-4			28.1				
RR191 M3-5			26.8	-11.6	-3.0		
RR191 M3-6			25.7				
RR191 M3-7			24.4	-12.3	-3.0		
RR191 M3-8			23				
RR191 M3-9			21.8	-12.7	-2.8	0.708872	0.000011
RR191 M3-10			20.3				
RR191 M3-11			19	-12.6	-2.2		
RR191 M3-12			17.8				
RR191 M3-13			16.1	-12.3	-1.4		
RR191 M3-14			14.8				
RR191 M3-15			13.6	-11.6	-0.9	0.708795	0.000012

RR191 M3-16	11.9		
RR191 M3-17	11	-11.2	-0.6
RR191 M3-18	9.3		
RR191 M3-19	7.7	-10.5	-0.7
RR191 M3-20	6.2		
RR191 M3-21	4.2	-9.5	-2.0
RR191 M3-22	2.4		

Table S3. $\delta^{18}\text{O}_{\text{VPDB}}$, $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of sequential tooth enamel bioapatite samples from Knossos.

^a Context abbreviations: MUM=Minoan Unexplored Mansion; RR=Royal Road.

^b Erj=enamel-root junction.

^c Estimated age of animal at slaughter based on tooth eruption and wear (after Payne 1973).

Sample ID	Species	$\delta^{18}\text{O}_{\text{VPDB}}$		$\delta^{13}\text{C}$	
		Mean	$\pm 2\sigma$	Mean	$\pm 2\sigma$
MUM70 M2	goat	-0.1	1.5	-10.8	0.3
MUM73 M2	goat	-0.3	1.0	-11.2	0.2
MUM78 M2	goat	-1.4	1.5	-11.5	0.4
RR188 M2	goat	-2.3	1.7	-10.8	0.3
RR188 M3	goat	-3.4	1.6	-10.9	0.2
MUM72 M2	sheep	-3.2	0.8	-11.9	0.8
MUM75 M2	sheep	-2.2	0.9	-11.2	0.8
RR 191 M2	sheep	-2.4	0.9	-10.8	0.5
RR 191 M3	sheep	-1.9	1.0	-11.5	1.0

Supplementary Table S4. Data for Figures 9 and 10.

Sample ID ^a	Species	Tooth	Payne Stage ^c	Distance from erj ^b (mm)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
MUM70 M2-1	goat	M2	E (2-3 years)	28.2	-11.1	-1.5	0.708899	0.000010
MUM70 M2-2				27				
MUM70 M2-3				26.1	-11.3	-1.0		
MUM70 M2-4				24.1				
MUM70 M2-5				22.7	-11.1	-0.1	0.708896	0.000011
MUM70 M2-6				21.2				
MUM70 M2-7				19.4	-10.9	1.3		
MUM70 M2-8				18.1				
MUM70 M2-9				16.6	-10.6	2.1		
MUM70 M2-10				14.9				
MUM70 M2-11				13.4	-10.3	1.5		
MUM70 M2-12				12.9				
MUM70 M2-13				10.5	-10.5	0.7		
MUM70 M2-14				9.2				
MUM70 M2-15				6.7	-10.7	-1.8		
MUM70 M2-16				5.4				
MUM70 M2-17				3.6	-11.0	-2.0	0.708979	0.000011
MUM70 M2-18				1.3				
MUM73 M2-1	goat	M2	E (2-3 years)	29.6	-10.9	-2.3	0.708958	0.000012
MUM73 M2-2				27.9				
MUM73 M2-3				26.4	-11.1	-1.4		
MUM73 M2-4				24.8				
MUM73 M2-5				23.2	-11.0	-0.7	0.2	
MUM73 M2-6				21.7				
MUM73 M2-7				20.4	-10.9	0.2		
MUM73 M2-8				19.4				

MUM73 M2-9				18.2	-10.9	0.1		
MUM73 M2-10				17.1				
MUM73 M2-11				15.8	-11.2	0.3		
MUM73 M2-12				14.6				
MUM73 M2-13				13.5	-11.4	0.9	0.709021	0.000012
MUM73 M2-14				11.9				
MUM73 M2-15				10.8	-11.3	0.8		
MUM73 M2-16				9.6				
MUM73 M2-17				8	-11.4	0.0		
MUM73 M2-18				6.8				
MUM73 M2-19				5.7	-11.4	-0.7	0.709045	0.000012
MUM73 M2-20				4.1				
MUM78 M2-1	goat	M2	D (1-2 yrs)	30.4	-11.4	-3.4		
MUM78 M2-2				29.1			0.709329	0.000009
MUM78 M2-3				27.8	-11.6	-3.3		
MUM78 M2-4				26.2				
MUM78 M2-5				24.8	-12.0	-3.3		
MUM78 M2-6				23.6				
MUM78 M2-7				22.1	-12.1	-2.5		
MUM78 M2-8				20.9				
MUM78 M2-9				19.6	-12.1	-1.7	0.709293	0.000014
MUM78 M2-10				18.3				
MUM78 M2-11				17.1	-11.6	-0.8		
MUM78 M2-12				16.1				
MUM78 M2-13				15	-11.0	-0.3		
MUM78 M2-14				14				
MUM78 M2-15				12.8	-11.2	0.4		
MUM78 M2-16				11.1			0.709241	0.000012
MUM78 M2-17				10.1	-11.1	0.3		

MUM78 M2-18				8.8				
MUM78 M2-19				7.3	-11.2	-0.2		
MUM78 M2-20				5.7				
MUM78 M2-21				4.5	-11.4	-1.0		
MUM78 M2-22				2.7				
RR188 M2-1	goat	M2	E (2-3 years)	27.9	-11.4	-3.5		
RR188 M2-2				26.8				
RR188 M2-3				25.2	-11.1	-2.7	0.708773	0.000012
RR188 M2-4				23.7				
RR188 M2-5				22.5	-11.0	-1.5		
RR188 M2-6				21.1				
RR188 M2-7				19.6	-10.9	-0.7		
RR188 M2-8				18.5				
RR188 M2-9				17	-10.7	-0.1	0.708671	0.000012
RR188 M2-10				15.8				
RR188 M2-11				14.4	-10.8	-0.3		
RR188 M2-12				13				
RR188 M2-13				11.7	-10.6	-1.0		
RR188 M2-14				10.2				
RR188 M2-15				8.8	-10.6	-2.2		
RR188 M2-16				7.2				
RR188 M2-17				6.5	-10.4	-4.4	0.70854	0.000010
RR188 M2-18				3.9	-10.6	-4.6		
RR188 M3-1		M3		33.3				
RR188 M3-2				31.7				
RR188 M3-3				30	-10.6	-4.3		
RR188 M3-4				28.6				
RR188 M3-5				27.3	-11.0	-4.8		
RR188 M3-6				26.1				

RR188 M3-7				24.7	-10.8	-4.7		
RR188 M3-8				23.5			0.708298	0.000011
RR188 M3-9				22.1	-11.2	-4.6		
RR188 M3-10				21				
RR188 M3-11				19.8	-11.2	-3.6		
RR188 M3-12				18.5				
RR188 M3-13				17.5	-11.2	-2.6		
RR188 M3-14				16			0.708407	0.000012
RR188 M3-15				14.8	-11.1	-1.0		
RR188 M3-16				13.3				
RR188 M3-17				12	-10.9	-0.8		
RR188 M3-18				10.6				
RR188 M3-19				9.1	-10.8	-1.8		
RR188 M3-20				7.4				
RR188 M3-21				5.9	-10.7	-3.8		
RR188 M3-22				4.4			0.708474	0.000011
RR188 M3-23				2.7	-10.8	-5.2		
MUM72 M2-1	sheep	M2	D (1-2 yrs)	22.7	-11.5	-3.3		
MUM72 M2-2				21.2				
MUM72 M2-3				19.3	-11.1	-3.8		
MUM72 M2-4				17.3				
MUM72 M2-5				15.8	-10.8	-4.0	0.709049	0.000010
MUM72 M2-6				14.3				
MUM72 M2-7				12.9	-11.3	-3.9		
MUM72 M2-8				11.7				
MUM72 M2-9				10.5	-12.1	-3.8	0.709046	0.000012
MUM72 M2-10				8.9				
MUM72 M2-11				7.5	-12.5	-3.1		
MUM72 M2-12				6				

MUM72 M2-13				4.3	-12.9	-2.2	0.709039	0.000012
MUM72 M2-14				2.7	-12.6	-1.8		
MUM75 M2-1	sheep	M2	E (2-3 years)	30.9	-11.1	-2.9		
MUM75 M2-2				29.5				
MUM75 M2-3				28.1	-11.7	-2.8		
MUM75 M2-4				26.8				
MUM75 M2-5				25.5	-12.0	-2.6		
MUM75 M2-6				24.6				
MUM75 M2-7				22.9	-12.1	-2.6	0.709017	0.000009
MUM75 M2-8				22				
MUM75 M2-9				20.8	-12.1	-2.2		
MUM75 M2-10				19.6				
MUM75 M2-11				18	-11.6	-1.2		
MUM75 M2-12				16.8				
MUM75 M2-13				15.8	-10.8	-0.7	0.70904	0.000008
MUM75 M2-14				14.1				
MUM75 M2-15				12.1	-10.3	-1.0		
MUM75 M2-16				10.2				
MUM75 M2-17				8.6	-9.9	-2.5		
MUM75 M2-18				7.1				
MUM75 M2-19				5.3	-10.1	-3.5	0.709026	0.000010
MUM75 M2-20				3				
RR191 M2-1	sheep	RR191 M2	E (2-3 years)	26.2	-10.0	-3.7		
RR191 M2-2				24.3			0.708899	0.000010
RR191 M2-3				22.9	-11.0	-3.4		
RR191 M2-4				21.5				
RR191 M2-5				20.1	-11.6	-3.2		
RR191 M2-6				18.6				
RR191 M2-7				17	-11.4	-2.0		

RR191 M2-8			15.5				
RR191 M2-9			14.1	-10.9	-1.7		
RR191 M2-10			12.9				
RR191 M2-11			11.8	-10.4	-1.4		
RR191 M2-12			11			0.708915	0.000013
RR191 M2-13			9.8	-10.2	-1.3		
RR191 M2-14			8.2				
RR191 M2-15			7.1				
RR191 M2-16			5.8				
RR191 M2-17			4.5	-10.6	-2.7		
RR191 M2-18			3			0.708869	0.000012
RR191 M2-19			2	-11.0	-2.3		
RR191 M3-1	sheep	RR191 M3	31.9				
RR191 M3-2			30.9			0.708913	0.000011
RR191 M3-3			29.6	-10.8	-2.9		
RR191 M3-4			28.1				
RR191 M3-5			26.8	-11.6	-3.0		
RR191 M3-6			25.7				
RR191 M3-7			24.4	-12.3	-3.0		
RR191 M3-8			23				
RR191 M3-9			21.8	-12.7	-2.8	0.708872	0.000011
RR191 M3-10			20.3				
RR191 M3-11			19	-12.6	-2.2		
RR191 M3-12			17.8				
RR191 M3-13			16.1	-12.3	-1.4		
RR191 M3-14			14.8				
RR191 M3-15			13.6	-11.6	-0.9		
RR191 M3-16			11.9			0.708795	0.000012
RR191 M3-17			11	-11.2	-0.6		

RR191 M3-18	9.3		
RR191 M3-19	7.7	-10.5	-0.7
RR191 M3-20	6.2		
RR191 M3-21	4.2	-9.5	-2.0
RR191 M3-22	2.4		

Table S3. $\delta^{18}\text{O}_{\text{VPDB}}$, $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of sequential tooth enamel bioapatite samples from Knossos.

^a Context abbreviations: MUM=Minoan Unexplored Mansion; RR=Royal Road.

^b Erj=enamel-root junction.

^c Estimated age of animal at slaughter based on tooth eruption and wear (after Payne 1973).

Figure Captions

Figure 1. Simplified geological map of Crete (A) and insets (B-D) with detailed geological formations, modern plant collection localities (cf. Table 1) and archaeological sites and regions mentioned in the text (general map after Kneuker et al., 2015; Papanikolaou and Vassilakis, 2010; Zulauf et al., 2016; inset B: IGME geological map, Herakleio Sheet 1996; inset C: IGME Epano Archanes Sheet 1994; IGME Tymbaki Sheet 1984; Siart et al., 2010; inset D: IGME Mochos Sheet 1989; IGME Agios Nikolaos Sheet 1987).

Figure 2. 2010-2017 average monthly temperature and precipitation from stations closest to areas relevant to present study (data source: National Observatory of Athens records, <http://meteosearch.meteo.gr/>; see Supplementary Table S1 for data used); (key: lines=temperature; bars=precipitation; solid black=Anogeia; grey=Tzermiado; dashed =Herakleio south near Knossos).

Figure 3. Sheep grazing on the rocky coastline north-east of Palaikastro (eastern Crete, July 2015).

Figure 4. Modern plant $^{87}\text{Sr}/^{86}\text{Sr}$ ratios grouped by region. Individual sample ratios overlaid by boxplots represent the median and interquartile range of $^{87}\text{Sr}/^{86}\text{Sr}$ for each location. Symbols coloured by geological unit (key in Figure 1); filled triangles: ligneous plants; open triangles: non-ligneous plants; stars: modern snail shells from Knossos (from Nafplioti 2008; 2011).

Figure 5. Left: sheep grazing endemic ‘nevrida’ (*Polygonum idaeum*) on the Nida polje (November 2013). Right: goats browsing evergreen oak on surrounding slopes (September 2005).

Figure 6. Effect of mean annual precipitation on $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of: a) non-ligneous plants and b) ligneous plants (precipitation data from the WorldClim database).

Figure 7. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (black symbols) and $\delta^{18}\text{O}_{\text{VPDB}}$ values (open symbols) of sheep and goat tooth enamel bioapatite from Knossos (ERJ = enamel-root junction).

Figure 8. $\delta^{18}\text{O}_{\text{VPDB}}$ (open symbols) and $\delta^{13}\text{C}$ values (black symbols) of sheep and goat tooth enamel bioapatite from Knossos (ERJ = enamel-root junction).

Figure 9. Average $\delta^{18}\text{O}_{\text{VPDB}}$ values and standard deviations of sampled archaeological teeth from Knossos (solid: goat; open: sheep; second mandibular molars [M_2], unless otherwise indicated).

Figure 10. Average $\delta^{13}\text{C}$ values and standard deviations of sampled archaeological teeth from Knossos (solid: goat; open: sheep; second mandibular molars [M_2], unless otherwise indicated).