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ORIGINAL PAPER

The Islamic cemetery at 33 Bartomeu Vicent Ramon, Ibiza: investigating diet and mobility through light stable isotopes in bone collagen and tooth enamel

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Abstract

The Balearic Islands occupy a central space in the western Mediterranean, at the maritime crossroads between North Africa, the Iberian Peninsula and the rest of southwestern Europe. As such, it is well placed to investigate changes in subsistence practices associated with the major cultural transitions following the arrival of Islamic rule. Stable carbon and nitrogen isotope analysis was carried out on bone collagen from the Islamic cemetery (ca. AD 950–1150) population excavated at 33 Bartomeu Vicent Ramon, Ibiza, including human ($n = 42$) and faunal remains ($n = 3$). Stable oxygen and carbon isotope analysis was also undertaken on human tooth enamel carbonate ($n = 6$), and six humans were directly radiocarbon dated, confirming the presence of two distinct burial phases. The collagen results emphasise a C_3-based diet, with variable but generally minor contributions from marine and/or C_4 foods. However, the enamel carbonate results indicate a far greater importance of C_4 crops than suggested by the collagen results, contributing up to 40% of energy intake. In keeping with previous studies of the region and period, the dietary contribution of marine protein is probably limited. A small number of outliers in both collagen and carbonate isotope results are identified, suggesting the presence of individuals originating elsewhere. The results are compared with those from previous investigations on the Balearics and the Spanish mainland, highlighting the complexity of factors—both cultural and methodological—affecting inter-regional dietary investigation.

Keywords Islamic Ibiza · Diet · Mobility · Stable isotope analysis · Radiocarbon dating

Introduction

Located off the eastern shore of the Iberian Peninsula, the Balearic Islands provide a window onto a host of political, cultural, social and economic changes taking place in medieval southwest Europe, primarily as a result of the shifting dominance of Islamic and Christian social, political, and cultural influences. Islamic influence on the Balearics began in the seventh century AD, but was greatly intensified when the islands were formally brought into the Umayyad by ‘Isam al-Khawlâni in AD 902. This was followed by an influx of settlers mainly of Berber origin from the mainland (al-Andalus) who would have encountered a sparsely populated island (Barceló 1997; Ferrer Abárzuza, 2014: 47). This no doubt facilitated the rapid colonisation of the entire island over only a few decades (Barceló 2005: 30), affecting both the countryside (Kirchner 2006: 128–132) and the town or *madina*. The settlers brought with them new foodstuffs, among which were ^{13}C-enriched C_4 plants such as sorghum and possibly sugarcane, as well as advanced irrigation systems that enabled the cultivation of crops on a scale far beyond that seen on the islands previously (Kirchner 2002, 2006, 2009; Kirchner and Retamero 2015; Retamero 2008; Watson 1983). The town of Eivissa at the beginning of the tenth century

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would have been a simple castle (Ramon 2000: 141; Marlière and Torres Costa in press), which then expanded into a more substantial urban centre in the twelfth century (Ferrer Abárzuza, 2014: 76). This new incoming population brought changes in agricultural technology, cuisine, religion, social structure and language (Glick 2005; Kirchner and Retamero 2015; Waines 1992; Watson 1983; Zaouali 2007). The Islamic period ended with the islands' conquest under the Catholic monarch James I of Aragón in 1229–1235 (Glick 2005), with Ibiza itself being invaded in 1235 in an expedition led by Guillem de Montgrí, archbishop of Tarragona (Abulafia 1994: 43).

In this paper, light stable isotope analyses of bone collagen ($\delta^{13}C$, $\delta^{15}N$) and tooth enamel ($\delta^{13}C_{ap}$, $\delta^{18}O_c$) are used to investigate diet and mobility at the Islamic necropolis recently excavated at the site 33 Bartomeu Vicent Ramon (33BVR), in the city of Eivissa, Ibiza (Fig. 1). We explore the impact of socio-political, cultural and economic changes on diet in relation to both earlier and later periods on the Balearic Islands as well as on the adjacent Spanish mainland. The excavated area of the necropolis appears to span the late tenth to mid-twelfth centuries, and so relates to one of the most dynamic and critical periods of the Spanish Middle Ages (Glick 2005: 37; Kaegi 2010).

The two interconnected research questions posed here relate firstly to the relationship between subsistence practices on the Balearic Islands, particularly Ibiza, and those of the mainland, and secondly to diachronic dietary trends in relation to the substantial wider social, cultural and political changes of the period. Given their common origins, it is expected that the medieval Islamic diets of the Balearic Islands were broadly comparable to those of mainland al-Andalus. Nevertheless, the insular position of the Balearic Islands, with easy access to marine resources, suggests the possibility of a distinct subsistence economy from that of the adjacent mainland regardless of period. In addition, the islands' port towns in particular might be expected to have had higher numbers of immigrants at any given time, some of whom would have died and been buried on the islands. Our study builds on previous work on both themes, which has increased substantially in recent years, allowing these wider comparisons to be made (Alexander et al. 2015; Fuller et al. 2010; Nehlich et al. 2012; Pickard et al. 2017; Salazar-García 2011; Salazar-García et al. 2014; van Strydonck et al. 2002, 2005; Ziriax 2017).

Bartomeu Vicent Ramon, Ibiza

In advance of new construction, an area of 240 m^2 was excavated at the former Sindicatos building, 33 Bartomeu Vicent Ramon, Eivissa in 2015 (Marí et al. 2016). In total, 125 burials were excavated from a necropolis that saw use between the tenth and twelfth centuries (Fig. 2). As dictated by Islamic burial practices, bodies were laid on their right sides, facing east, with no accompanying grave goods (Fig. 3). No directly associated settlement has been discovered. The current site was part of a larger cemetery or *maqbara,* which would also encompass a number of other excavated sites in the vicinity such as those in Avenida España 3 (Kranioti et al. 2015; Girdwood et al. 2015; Martín Parrilla and Graziani Echávarri 2009) and that at the site of en Hort des Pilarets (Roig 2015; Marlière and Torres in press). Full osteological analysis of the skeletal assemblage is still underway.

Diet in early medieval Spain

Foodways are embedded in culture and in politics and can be used to mark distinct identities (Counihan 1999; Goody 1982; Watson and Caldwell 2004). These can be especially powerful when culture and politics interact with religion, as was the case in medieval Spain (Zaouali 2007). The variety of foodstuffs available in medieval Spain presents a challenge for isotopic studies of diet, which, as discussed below, are limited to distinguishing certain broad food categories, and even then are prone to issues of equifinality in interpretation. Other lines of evidence are therefore important and include archaeobotanical and zooarchaeological findings, as well as early historical documents. These sources are not without their own biases—for example, while providing invaluable detail, the available medieval texts frequently focus on the elite, on urban settings and on special aspects such as religious restrictions rather than on the social, cultural and economic realities of day-to-day subsistence practices (Bolens 1978; Constable 2013; Grewe 1981; Zaouali 2007)—but used in combination with the isotopic evidence they can provide far greater insights than each on its own. The following section very briefly summarises some of this evidence.

Both Muslims and Christians valued wheat (*Triticum* spp.) highest among the cereals, generally followed by barley (*Hordeum vulgare*) and rice (*Oryza sativa*). The importance of wheat and hulled barley is made clear by their dominance in the archaeobotanical record of the period, appearing at numerous sites regardless of their religious or socioeconomic status (Alonso 2005; Alonso et al. 2014; Peña-Chocarro et al. 2018). Less desirable cereals included rye (*Secale cereale*) and the C_4 crops millet (*Panicum miliaceum* and *Setaria italica*) and sorghum (*Sorghum bicolor*) (Alonso 2005; Alòs et al. 2007; de Castro 1993; García Marsilla 1993; García-Sánchez 1995, 1996, 2002, Moreno-Larrazabal et al. 2015; Rubio 1995; Tomás 2009; Watson 1983). These may have seen greater use by the poor, and as livestock fodder and poultry feed. Pulses, including peas (*Pisum sativum*), broad beans (*Vicia faba*), lentils (*Lens culinaris*) and chickpeas (*Cicer arietinum*) are present but generally do not feature strongly in the medieval period, though they may have been an important source of protein on occasion for the less well off and again were also

Fig. 1 Map of the Balearic Islands and adjacent Spanish mainland with inset view of the Pityusic Islands (Ibiza and Formentera) showing locations of sites mentioned in the text

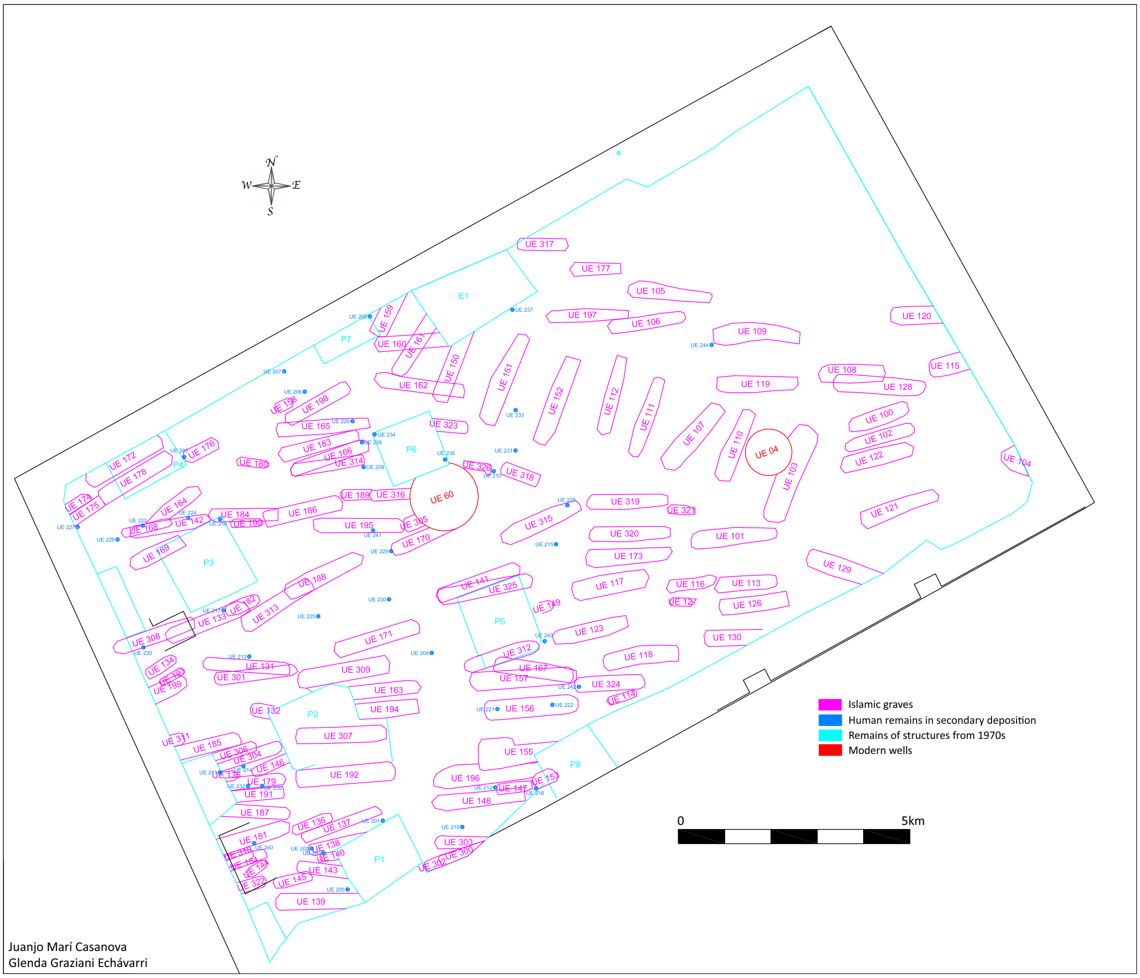

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Fig. 2 Plan of the archaeological excavations at 33 Bartomeu Vicent Ramon. Adapted from Marí et al. (2016)

used as animal fodder (García-Sánchez 2002). Olives (*Olea europaea*) also made an important dietary contribution, especially in the form of oil, and nuts and fruits were widely consumed, though featuring more strongly in Islamic cuisine. While there is some debate over the details, a number of new crops are thought to have been introduced to the Iberian Peninsula in the Islamic period (Watson 1983). Millets, sometimes considered as among these introductions, were already present since at least the Bronze Age, and feature regularly in Roman period sites (Peña-Chocarro et al. 2018). Sorghum and rice, along with sugarcane (*Saccharum officinarum*), on the other hand, were introduced in the Islamic period, and certainly feature in the historical documentation (Glick 2005). Perhaps surprisingly, then, no remains of either sorghum or rice have yet been identified in archaeobotantical assemblages from the Iberian Peninsula, though sorghum has been found in medieval sites in southern France (Peña-Chocarro et al. 2018).

Religious and cultural food preferences and prohibitions are often more pronounced in animal than in plant foods. Lamb, kid and chicken were the most highly regarded meats in medieval al-Andalus; wild game was consumed where available, and sheep and goat milk and cheese were common

Fig. 3 Grave S101 at 33 Bartomeu Vicent Ramon, showing typical Islamic burial position, lying supine on the right side and facing east towards Mecca

fare (de Castro 1993; Gallart et al. 2005; Garcia et al. 2004; Salas-Salvadó et al. 2006; Waines 1992). Beef, on the other hand, was more strongly associated with Christian cuisine. Fish were not a high status food, but were frequently consumed along the rivers and coasts, as well as being dried and salted for trade inland, though it is difficult to quantify their importance relative to other foods from either textual or archaeological sources. Nevertheless, seafood may have been more important in Mediterranean Spain than in most other parts of the Islamic world (Zaouali 2007). For Christians, fish consumption had religious associations, given the considerable number of holy days such as Lent and frequent ‘fasting’ periods, meaning abstinence from meat (Grumett and Muers 2010; Tomás 2009). Islam had no such religious prohibitions against meat at any time, though of course it prohibited the eating of pork, which was popular among Christian communities (de Castro 1993; García-Sánchez 1996; Waines 1992). However, the extent to which such religious restrictions and admonitions are adhered to can vary considerably over time and by both household and individual (Grumett and Muers 2010; Tomás 2009).

Stable isotope analysis and past diets

All plants exclusively utilise one of three metabolic pathways in order to fix carbon from atmospheric CO_2. The two most common pathways are known as C_3 and C_4, while the third, Crassulacean Acid Metabolism (CAM), is relatively rare and not pertinent to this study (Pearcy and Ehleringer 1984). Both C_3 and C_4 plants are ^{13}C-depleted relative to the international standard VPDB (defined as 0‰), but C_4 plants discriminate less against the heavier ^{13}C isotope and so the two pathways can be easily distinguished. Preindustrial C_3 plants in southern Europe will average approximately − 25‰, while C_4 plants will average approximately − 11‰. Thus, stable carbon isotope ratios (δ^{13}C) can be used to identify and semi-quantify the dietary contributions of C_3 and C_4 foods (Lee-Thorp 2008; Schwarz and Schoeninger 1991). In Europe, the vast majority of both domestic and wild plants consumed make use of the C_3 photosynthetic pathway. Thus, the introduction of C_4 crops, whether consumed directly or indirectly via animal tissues and secondary products (i.e., dairy), will lead to a marked shift to more ^{13}C-enriched values in human consumers. Marine organisms will be intermediate between the two main terrestrial photosynthetic pathways. Thus, it is not always possible to distinguish between marine and C_4 contributions to diet using δ^{13}C alone. This is where stable nitrogen isotopes (δ^{15}N) have an important role.

Each trophic level in the food chain is associated with an increase in δ^{15}N ratios of 3–5‰ (Ambrose 1991; Bocherens and Drucker 2003; DeNiro and Epstein 1981; Schoeninger and DeNiro 1984; Sponheimer et al. 2003; O’Connell et al. (2012) have suggested this could be as high as 6‰ in humans). Being longer and more complex than terrestrial food chains, aquatic food chains have the potential for many more trophic levels, and so can impart higher δ^{15}N values to human consumers. This is one means of differentiating C_4 and marine protein consumption. Interpretation is complicated, however, by the fact that manuring can increase δ^{15}N values in cereals by 2.6 to 8.0‰, depending on its intensity (Bogaard et al. 2007). Countering this, the consumption of pulses can significantly lower δ^{15}N values. These nitrogen-fixing plants have a symbiotic relationship with denitrifying rhizobacteria, fixing nitrogen (N_2) directly from the atmosphere with little or no fractionation so that their δ^{15}N values that closely resemble those of the standard AIR, i.e., near 0‰ (Fraser et al. 2011; Virginia and Delwiche 1982).

As nitrogen is only found in protein, it only informs on that dietary component. Stable carbon isotope measurements on bone collagen are biased towards dietary protein, to a degree that will depend mainly on the quantity and quality of protein in the diet (Ambrose and Norr 1993; Jim et al. 2006). The lower these are, the greater will be the dietary contribution of carbohydrates and lipids to the de novo synthesis of non-essential amino acids. Measurements made on the mineral component, however, reflect the proportional contributions of all three macronutrients (Ambrose and Norr 1993). However, this fraction is less frequently used in archaeological studies because of its greater susceptibility to diagenetic alteration in the burial environment. Enamel is much more resistant than bone or dentine in this respect, and so offers more reliable results in most circumstances (Wang and Cerling 1994). There is some debate concerning whether $\delta^{13}C_{ap}$ measurements in enamel and bone carbonate (bioapatite) are directly comparable, with some experiments suggesting an offset of ca. + 2.3‰ for enamel compared to bone (Warinner and Tuross 2009). Other studies, however, have not found this offset (Loftus and Sealy 2012), nor is there any theoretical reason that the two tissues should differ in this respect (Lee-Thorp et al. 1989), and so its applicability remains uncertain.

Stable oxygen isotope (δ^{18}O) analysis has been used extensively to study mobility in both fauna and humans. The lighter isotope (^{16}O) is preferentially evaporated from seawater whilst the heavier isotope (^{18}O) is preferentially removed during precipitation, causing δ^{18}O values to become progressively more negative with distance from the source (Darling et al. 2003; Körner et al. 1991). Because δ^{18}O in drinking water is strongly related to local precipitation, measurements made on humans can be compared against environmental precipitation and drinking water data in order to determine whether or not they are consistent with a local origin (Darling et al. 2003). As well as drinking water, oxygen in food will also contribute to δ^{18}O. For humans, cultural practices such as brewing and stewing can further complicate matters, causing moderate to strong ^{18}O-enrichment (Bretell et al. 2012).

Analysis of δ^{18}O is usually carried out on tooth enamel, again, because of its greater resistance to diagenesis. Enamel hydroxyapatite forms from infancy to adolescence, becoming biologically inert after formation, and so its isotopic composition does not alter once formed. The timing of mineralisation varies depending on the tooth: the first molar crown begins to form in utero and is complete around age 3, the second molar forms between 2.5 and 8 years, and the third molar forms between 8 and 14 years (Hillson 2005).

Materials and methods

Rib samples from 46 individuals from 33BVR were selected for analysis of δ^{13}C and δ^{15}N. Included are adults (age > 20 years), juveniles (age 13–20), children (age 2–13) and infants (age < 2). Infants and young children will be subject to a ‘nursing effect’ resulting in higher δ^{15}N values than the other age categories (Fogel et al. 1989, Fuller et al. 2006). Enamel from the permanent molars of six individuals was analysed for carbonate $\delta^{13}C_{ap}$ and $\delta^{18}O_c$. Since the excavated area was a necropolis, faunal remains were scarce, and are limited here to a single cow, bird (probable chicken) and ovicaprid. These samples were combined with faunal data from the wider region to provide a baseline for comparison with the human results. Six individuals were selected for ^{14}C AMS dating, to assess the absolute difference between phase 1 and phase 2 graves as determined stratigraphically, and whether those individuals most enriched in ^{13}C were contemporary with the others.

Collagen extraction from the 46 human and three faunal samples was carried out following a modified Longin method (Richards and Hedges 1999). Briefly, samples were cleaned using a shot blaster before being weighed out (100 mg) and demineralised in 10 ml of 0.5 M HCl at 5 °C over the course of 2 to 5 days. They were then repeatedly rinsed in milliQ water before being transferred into sealed tubes containing a pH 3 HCl solution at 75 °C for 48 h. The gelatinised sample solution was collected using 9-µm EZEE filters (Elkay, UK). Samples were freeze-dried and approximately 1 mg of the resulting ‘collagen’ was placed into tin capsules. Measurements were undertaken in a Europa 20/20 continuous flow isotope ratio mass spectrometer. Alanine was used to control for machine drift, and two internal collagen standards—cow and seal—were used to provide a two-point calibration of the results (see Coplen et al. 2006), referenced to the international standards VPDB and AIR for δ^{13}C and δ^{15}N, respectively. Samples were measured in duplicate and averaged. Measurement precision is on the order of ± 0.2‰ for both δ^{13}C and δ^{15}N. Collagen quality is assessed through collagen yield and C:N ratios (Ambrose 1990, DeNiro 1985; van Klinken 1999). While a C:N range of 2.9–3.6 is often used in stable isotope studies (DeNiro 1985), we use a slightly more restricted range of 2.9–3.5, since it was observed that those samples with ratios of 3.6 or more often differed by > 0.5‰ between duplicate measurements in one or other isotope.

Enamel from first (BVR162), second (BVR104, BVR155, BVR157, BVR161) and third (BVR150) molars was sampled for $\delta^{13}C_{ap}$ and $\delta^{18}O_c$ analysis. Second molars were preferred, though one third and one first molar were also included, the latter of which could be subject to a small nursing enrichment (White et al. 2004; Wright and Schwarcz 1998; though see Murphy et al. 2007). Enamel was removed using a tungsten drill bit across the entire length of each sample (from crown to root) to provide a long-term average signal. The samples were treated with 2–3% NaOH for 24 h to remove contaminants, before the addition of 0.1 M acetic acid for 4 h to remove exogenous carbonate (cf. Balasse 2002). Powder weighing 600–750 µg was then reacted with 100% phosphoric acid at 90 °C in a VG Isogas Prism II mass spectrometer. Both $\delta^{18}O_c$ and $\delta^{13}C_{ap}$ are reported relative to the international VPDB standard.

Radiocarbon dating was carried out at the Oxford Radiocarbon Accelerator Unit (ORAU), following the protocols in Brock et al. (2010), using the same collagen prepared for stable isotope analysis (note that this did not include the use of an ultrafiltration step). A Bayesian model is employed to interpret the results making use of the stratigraphic relationships found between some of the graves (Bronk Ramsey 2009).

Data were assessed for normality using Shapiro-Wilk tests and then subjected to parametric (Student’s *t* test) or non-parametric (Mann-Whitney *U* test) statistical tests as appropriate. Tests were undertaken in SPSS and StatPlus. A Bonferroni post-hoc correction to the standard critical *p* level ($\alpha = 0.05$) is applied in cases where multiple simultaneous comparisons are made ($\alpha' = \alpha/k$, where $k =$ the number of groups being compared).

Results

Stable isotopes

Four human samples failed to meet the C:N criterion (2.9–3.5) for well-preserved collagen, leaving 42 individuals (Table 1; Fig. 4). The three faunal samples yielded acceptable collagen. The overall human results exhibit mean values of − 18.6 ± 0.8 and 10.8 ± 0.8‰ for δ^{13}C and δ^{15}N, respectively (Table 2). There are no significant differences between the adult/juvenile males and females in either δ^{13}C (Mann-Whitney *U* test, $Z = 1.64$, $p = 0.244$), or δ^{15}N (Student’s *t* test, $t = 0.202$; $p = 0.842$). While there is an impression that phase 2 contains more individuals slightly enriched in ^{13}C than phase 1, this

Table 1 Stable carbon and nitrogen isotope results, demographic and stratigraphic information for the 48 individuals from 33BVR. Sex: *F* females, *M* male. *I* indeterminate. Age: *A* adult, *J* juvenile, children are given midpoint of estimated age range. Samples marked with asterisk have been AMS ^{14}C dated

Grave	Collagen yield (%)	C:N	$\delta^{13}C_{coll}$	$\delta^{15}N_{coll}$	Sex	Age	Phase
BVR196	2.3	3.2	−19.1	9.6	F	A	1
BVR301*	2.4	3.2	−19.4	10.6	F	J	1
BVR133	3.2	3.2	−19.0	10.8	F	A	2
BVR150	2.9	3.2	−17.8	11.4	F	A	2
BVR155	4.0	3.2	−18.9	11.5	F	A	2
BVR156	4.9	3.3	−18.7	10.6	F	A	2
BVR157	2.9	3.3	−18.8	10.8	F	A	2
BVR109	5.3	3.2	−18.9	10.9	F	A	–
BVR137	4.8	3.2	−18.8	10.4	F	A	–
BVR183	2.6	3.5	−19.2	9.3	F	A	–
BVR186	2.7	3.2	−19.4	10.5	F	A	–
BVR187	2.3	3.2	−18.6	10.6	F	A	–
BVR320	1.3	3.4	−19.8	10.7	F	A	–
BVR303	3.1	3.2	−18.8	10.6	M	A	1
BVR103	4.9	3.3	−17.4	10.9	M	A	2
BVR107	4.2	3.3	−19.1	11.1	M	A	2
BVR131*	5.0	3.3	−19.3	10.4	M	J	2
BVR151	4.8	3.3	−17.8	10.8	M	A	2
BVR101	3.7	3.3	−18.6	11.1	M	A	–
BVR117	4.9	3.3	−18.9	10.7	M	A	–
BVR120	1.8	3.3	−18.9	10.8	M	A	–
BVR170	3.3	3.2	−18.8	10.2	M	A	–
BVR173	2.1	3.3	−18.9	10.0	M	A	–
BVR195	2.7	3.2	−19.5	9.6	M	A	–
BVR319	3.2	3.2	−18.7	10.6	M	A	–
BVR115	3.5	3.2	−18.4	11.5	M	J	–
BVR123	0.7	3.4	−19.2	9.4	M	J	–
BVR162	3.0	3.3	−18.9	11.3	I	A	1
BVR308*	4.8	3.2	−18.8	11.2	I	J	1
BVR161*	5.0	3.2	−16.9	10.8	I	A	2
BVR167	4.0	3.2	−18.4	10.9	I	A	2
BVR139	5.0	3.2	−19.2	10.6	I	A	–
BVR181	2.8	3.3	−18.2	11.6	I	A	–
BVR198	3.2	3.2	−18.8	10.6	I	A	–
BVR104	2.0	3.3	−15.3	11.3	I	J	–
BVR119	2.4	3.2	−18.0	11.0	I	J	–
BVR113*	4.2	3.2	−18.5	10.9	I	*c*8	–
BVR116	3.2	3.3	−18.9	9.8	I	*c*3	–
BVR168	3.0	3.4	−19.0	11.5	I	*c*3	–
BVR176	2.8	3.2	−18.9	11.4	I	*c*4	–
BVR318	2.1	3.2	−18.1	13.0	I	*c*4	–
BVR321	1.1	3.4	−18.6	13.3	I	*c*1.5	–
Rejected							
BVR105	1.0	4.7	−20.3	8.3	M	A	–
BVR188	2.6	3.6	−18.8	10.2	M	A	–
BVR197	3.3	3.6	−19.0	10.3	M	A	–
BVR313	1.2	3.6	−20.0	9.5	M	A	–
Fauna							
Cattle	2.9	3.3	−21.7	4.6			–
Chicken?	3.2	3.3	−18.9	9.7			–
Ovicaprid	3.2	3.4	−20.4	5.1			–

is not statistically significant (δ^{13}C: Mann-Whitney, $Z = 1.25$; $p = 0.126$; δ^{15}N: heteroscedastic Student's *t* test, $t = 0.912$; $p = 0.404$). As would be expected as a result of the nursing effect, infants and young children (ranging from 1 to 2 to 3.5–4.5 years of age) exhibit significantly higher δ^{15}N values than the other combined ages (Mann-Whitney *U* test, $Z = 2.10$; $p = 0.036$). This is even clearer if sample BVR116 is omitted, with its anomalously low result of 9.8‰, compared to the mean of 12.3 ± 1.0‰ for the remaining four infants. There is no corresponding difference in δ^{13}C.

The δ^{13}C ratios of the single cattle (−21.7‰) and ovicaprid (−20.4‰) samples indicate entirely C_3 diets, while that of the

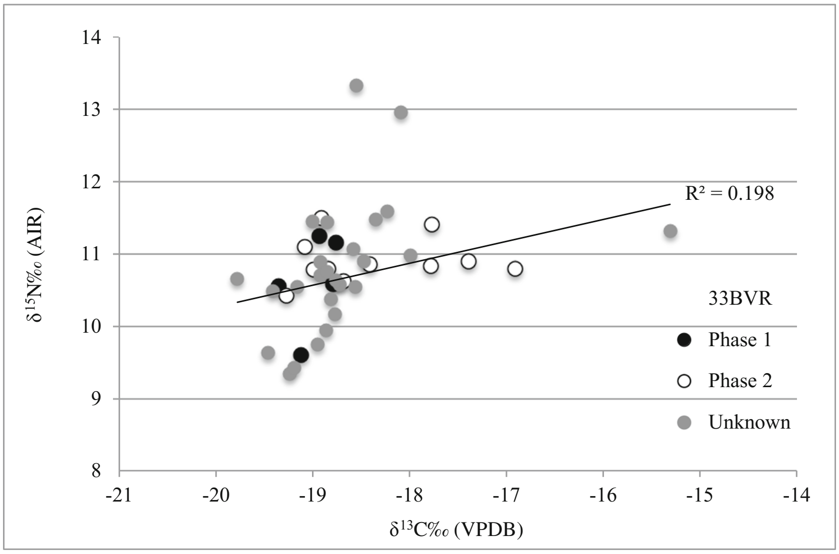


Fig. 4 Bone collagen δ^{13}C and δ^{15}N results from 33BVR by phase. The regression line ($r^2 = 0.198$, $p = 0.006$, $n = 37$) refers to adult/juveniles only and so excludes two infants with high δ^{15}N values as well as three other children age ca. 3 years

single bird (chicken?) is slightly elevated (− 18.9‰), suggest some contribution of C_4 grain and/or marine foods. Its relatively high δ^{15}N value (9.7‰) might be interpreted as supporting the latter, but birds can have a highly varied diet including ^{15}N-enriched insects, so that this cannot be assumed.

The $\delta^{18}O_{cVPBD}$ results average − 5.7 ± 1.3‰. Measurements on carbonate relate in a predictable way to those made on phosphate and can be converted to facilitate comparison with other studies (e.g., Guede et al. 2017), and both can be converted to the expected values for ingested water (Chenery et al. 2012), although each conversion introduces additional uncertainty (Pollard et al. 2011) (Table 3). The $\delta^{13}C_{ap}$ carbonate results average − 9.6 ± 1.6‰. Using a diet-consumer fractionation of ca. 9.5‰ for bone (Ambrose and Norr 1993) would equate with an average bulk dietary intake (i.e., including protein, carbohydrate and lipid) value of ca. − 19.1‰, significantly elevated above the expected value of ca. − 25‰ for a purely C_3-based diet. An adjustment of ca. 2.3‰ for the enamel-bone apatite difference suggested by Warinner and Tuross (2009) would reduce this estimated diet value to − 21.4‰, though as noted above the need for this step is not yet clear.

Radiocarbon dating

The six radiocarbon dates fall as expected within the tenth to twelfth centuries (Table 4; Fig. 5). As there is limited evidence for the contribution of marine foods (see below), it is unlikely that there is a significant marine reservoir effect to take into account. A Bayesian model placing the four dated graves assigned to phases 1 and 2 in a contiguous sequence suggests that the phases are separated by an interval of 0 to 80 years (95.4% confidence). Phase 1 may include individuals from the first or second generation after the conquest of 902. The remaining two ^{14}C determinations cannot be assigned stratigraphically, but their results are more consistent with Phase 2. There are two few dates to usefully discuss the overall modelled start and end date ranges.

Discussion

Diet and mobility at 33 Bartomeu Vicent Ramon

The $\delta^{13}C_{coll}$ mean of − 18.6 ± 0.8 at 33BVR suggests a diet dominated by terrestrial C_3 protein with a variable but

Table 2 Summary of human stable isotope results from 33 Bartomeu Vicent Ramon

Group	$\delta^{13}C_{coll}$	±	$\delta^{15}N_{coll}$	±	*n*	$\delta^{13}C_{ap}$	±	$\delta^{18}O_c$	±	*n*
Females	− 19.0	0.5	10.6	0.6	13					
Males	− 18.7	0.6	10.5	0.6	14					
Adult/adol.	− 18.6	0.8	10.7	0.6	36					
Child/infant	− 18.7	0.3	11.6	1.3	6					
All individuals	− 18.6	0.8	10.8	0.8	42	− 9.6	1.6	− 5.7	1.3	6
Phase 1	− 19.0	0.2	10.6	0.7	5					
Phase 2	− 18.4	0.8	10.9	0.3	11					

Table 3 Enamel $\delta^{13}C_{ap}$ and $\delta^{18}O_c$ values with conversions to drinking water values, using the formulae: $\delta^{18}O_{cVSMOW} = (1.03091 \times \delta^{18}O_{cVPDB}) + 30.91$; $\delta^{18}O_p = (1.0322 \times \delta^{18}O_c) - 9.6849$; $\delta^{18}O_{dwVSMOW} = (1.590 \times \delta^{18}O_{cVSMOW}) - 48.634$ (Chenery et al. 2012; Daux et al. 2008)

Grave	$\delta^{13}C_{coll}$	$\delta^{15}N_{coll}$	tooth	$\delta^{13}C_{apVPBD}$	$\delta^{18}O_{cVPDB}$	$\delta^{18}O_{cVSMOW}$	$\delta^{18}O_{pVSMOW}$	$\delta^{18}O_{dwVSMOW}$
BVR150	− 17.8	11.4	M3	− 11.2	− 7.5	23.2	14.2	− 11.8
BVR157	− 18.8	10.8	M2	− 11.0	− 6.6	24.1	15.2	− 10.3
BVR161	− 16.9	10.8	M2	− 10.0	− 6.2	24.5	15.6	− 9.6
BVR162	− 18.9	11.3	M1	− 10.2	− 5.3	25.4	16.6	− 8.2
BVR104	− 15.3	11.3	M2	− 8.1	− 5.0	25.8	16.9	− 7.7
BVR155	− 18.9	11.5	M2	− 7.3	− 3.7	27.1	18.3	− 5.5
$\overline{X}$ =	− 17.8	11.2		− 9.6	− 5.7	25.0	16.1	− 8.8
SD =	1.4	0.3		1.6	1.3	1.4	1.4	2.2

generally minor contribution of C_4 and/or marine foods. A common means of deciding between the latter two alternatives is to determine whether or not there is a significant positive correlation between $\delta^{13}C$ and $\delta^{15}N$, since, as noted above, trophic levels will be substantially higher in most marine systems compared to terrestrial systems (Richards and Hedges 1999). This is particularly so, since the isotopic data for fauna from the region (see below) suggest that domestic stock generally were not being fed C_4 crops or waste, implying that any C_4 crops would have been directly consumed by humans. There is a weak but significant positive correlation ($r^2 = 0.198$; $p = 0.006$) between $\delta^{13}C$ and $\delta^{15}N$, suggesting that marine foods may have featured in the diets of some individuals (Fig. 3). The weakness of this relationship itself suggests that C_4 crops are a likely confounding factor.

To explore diets at 33BVR further, it is necessary to compare the human results with a faunal baseline. Given the small number of faunal samples available from the site itself, we draw upon previously published faunal data from the wider region (Table 5). We recognise that this is not ideal, as both spatial and temporal differences in environments and in animal management practices can affect stable isotope results. Nevertheless, this does at least provide a starting point for comparison. The mean $\delta^{13}C$ value of − 19.6 ± 1.3‰ for the combined herbivores clearly indicates that these animals were predominately C_3 consumers. Given that a significant contribution of C_4 plants is only evident in two cattle and two poultry (*Gallus*) samples (Alexander et al. 2015), we can safely assume that any elevated ^{13}C ratios measured in human tissues indicate either direct consumption of C_4 foods or marine foods.

The apparently minimal contribution of marine foods raises a question regarding the mean $\delta^{15}N$ value of 10.7 ± 0.6‰ for post-weaning age individuals at 33BVR, as this is ca. 5‰ higher than ovicaprids, averaging 5.5 ± 2.0‰. While falling within the upper range of the expected trophic level shift of 3–5‰, this would require that all protein consumed was animal-based, which is problematic given the known contribution of both cereals and ^{15}N-depleted legumes to medieval Mediterranean diets. A number of possible explanations can be considered. Firstly, high-trophic-level foods may not be adequately represented in the limited faunal database. The minor contribution of marine protein could be emphasised in $\delta^{15}N$ over $\delta^{13}C_{coll}$, recalling that the latter will to some degree reflect carbohydrates and lipids as well as proteins (cf. Craig et al. 2009). Ovicaprids are the most important animals in Islamic period diets, but they show a wide range of $\delta^{15}N$ values, and would be highest for the culturally favoured suckling lamb and kid due to the nursing effect. Surprisingly, pigs are only slightly higher in $\delta^{15}N$ than ovicaprids, and in any case would not be expected to feature significantly in Islamic communities due to strong religious proscriptions, whether on Ibiza or on the mainland (Alexander et al. 2015; Antunes 1996; Benito 2006; Davis 2006; Lentacker and Ervynck 1999; Morales et al. 1988). Another potentially important food source is poultry (both meat and eggs), which exhibit substantially higher $\delta^{15}N$ values that all the herbivores,

Table 4 Radiocarbon dating results on human bone collagen from 33BVR. Calibrated in OxCal v4.2 (https://c14.arch.ox.ac.uk/oxcal/) using IntCal13 (Reimer et al. 2013)

Sample	Lab code	^{14}C yr	±	Phase	$\delta^{13}C$	cal AD (95%)		modelled AD	
BVR308	OxA-V-2727-54	1104	23	1	− 18.8	890	990	915	1020
BVR301	OxA-V-2727-53	1053	22	1	− 19.4	902	1025	970	1020
BVR131	OxA-V-2727-51	980	22	2	− 19.3	1014	1153	1010	1145
BVR161	OxA-V-2727-52	914	22	2	− 16.9	1034	1168	1025	1135
BVR104	OxA-V-2737-25	961	26	2?	− 15.9	1020	1155	1020	1150
BVR113	OxA-V-2727-50	946	22	2?	− 18.5	1027	1155	1025	1150

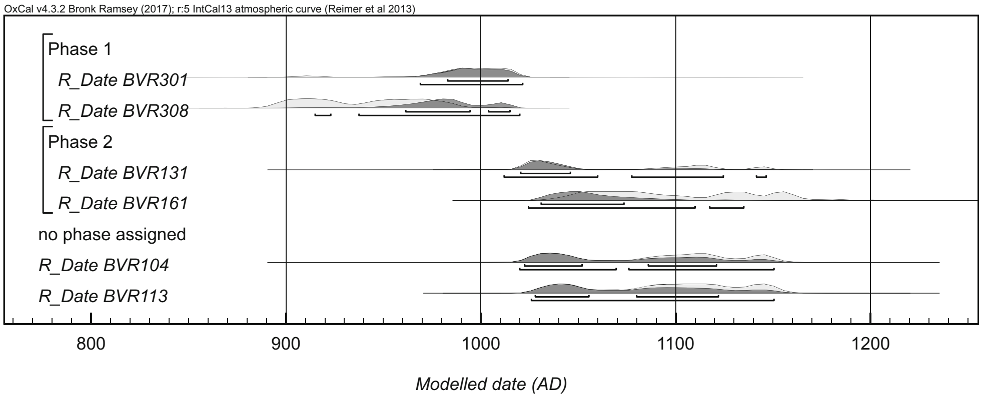


Fig. 5 Modelled radiocarbon dates (OxCal v4.3.2)

averaging 8.7 ± 0.9‰ (Table 5). Secondly, it may be that the trophic level shift for humans is nearer to 6‰ (O'Connell et al. 2012), though even this would reduce rather than eliminate the problem. Finally, the manuring of arable fields would lead to ^{15}N- enriched crops that might be indistinguishable from animal protein, obviating the problem of the unreasonably high contribution of animal protein required to account for the human δ^{15}N results (Alexander et al. 2015; Bogaard et al. 2007). Any combination of these factors could account for the moderately high elevation in human δ^{15}N values relative to the available faunal data.

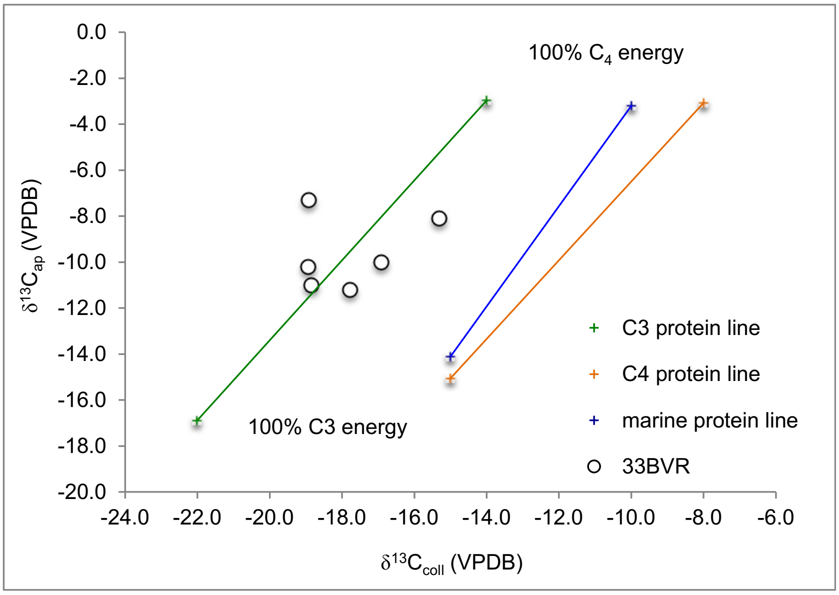
Given its central importance to our study, the potential contribution of C_4 foods requires additional discussion. Using human consumer endpoints of − 19.5 and − 6‰ for C_3 and C_4 consumers, respectively (based on faunal data from Table 5, and values of ca. 11‰ for millet from Tafuri et al. (2009), plus 5‰ for diet to bone collagen fractionation) and given the overall human mean δ^{13}C value of − 18.8‰, a simple linear extrapolation estimates the average C_4 protein contribution to be minimal, on the order of ca. 5%. Some individuals, however, may have made greater use of C_4 foods, most notably BVR104, with a $\delta^{13}C_{coll}$ value of − 15.3‰, more than four standard deviations above the site mean, and suggesting a C_4 contribution of ca. 30‰ (if marine foods are not taken into account, which is a plausible scenario given that the δ^{15}N value for this individual is raised above the mean by only 1 SD). Given the limited evidence for ^{13}C-enriched fauna in the study region, we can infer that humans were mainly consuming millet and/or sorghum directly, though generally only in small quantities. It is perhaps surprising that the impact of millet and sorghum is not greater, but this has been noted in other studies focussing on collagen (see below). However, their contribution may be underestimated if the diet contained adequate animal protein, since plant foods contain relatively less and lower quality protein, and so may be underrepresented in isotopic measurements on bone collagen (this is particularly so for sugarcane, with very low crude protein content, though whether this crop was cultivated on Ibiza specifically is not known).

Table 5 Faunal δ^{13}C and δ^{15}N values on bone collagen from the western Mediterranean (sources: this study; Alexander et al. 2015; Fuller et al. 2010; Pickard et al. 2017; Salazar-Garcia 2011; Salazar-Garcia et al. 2014)

Fauna	δ^{13}C, $\bar{X}$ ± SD	δ^{15}N, $\bar{X}$ ± SD	*n*
Ovicaprid	− 19.7 ± 0.7	5.5 ± 2.0	32
Cow	− 19.3 ± 2.2	7.2 ± 1.2	12
Herbivores	− 19.7 ± 1.3	6.0 ± 1.9	44
Pig	− 19.8 ± 1.4	5.8 ± 0.7	4
Bird	− 17.7 ± 2.1	8.7 ± 0.9	10
Dog	− 18.8 ± 0.3	10.3 ± 0.7	24
Cat	− 8.1 ± 1.5	9.2 ± 0.5	10

Measurements on enamel carbonate, however, reflect whole diet (Ambrose and Norr 1993), and the average $\delta^{13}C_{ap}$ value of − 9.6‰ is consistent with a C_4 intake of approximately 42% (based on a simple linear extrapolation between C_3 and C_4 plant endpoints of − 25 and − 11‰, respectively, and a diet-bioapatite spacing of 9.5‰). Any contribution of fish and shellfish would mean that this estimate is itself too high. Nevertheless, it seems clear that there was in fact a significant component of C_4 cereals in the diets of medieval Islamic population on Ibiza. Plotting the $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$ results against the model developed by Kellner and Schoeninger (2007) places the 33BVR results near the C_3 protein line and intermediate between C_3 and C_4 energy endpoints, though nearer the former (Fig. 6). The dominance of C_3 protein is clear, and will derive from a combination of meat and dairy, as well as eggs, along with C_3 cereals. Given the expected predominance of C_3 cereals, especially wheat, and the presumed secondary but important contribution of olives, nuts and fruits—all C_3 plants— in medieval Islamic diets, the high level of C_4 consumption inferred from the enamel measurements is perhaps surprising. Even assuming that there is indeed a bone-enamel offset of + 2.3‰ as proposed by Warinner and Tuross (2009), the C_4 energy contribution would still be significant, although it would be reduced to

Fig. 6 The 33BVR $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$ results plotted against Kellner and Schoeninger's (2007) model to distinguish C_3, C_4 and marine sources of protein and energy



ca. 25%. Further research on this assemblage, with additional enamel samples in particular, may help resolve the matter.

The average $\delta^{18}O_c$ value of − 7.3 ± 1.3‰ can be converted into an estimated $\delta^{18}O_{VSMOW}$ value of − 8.9 ± 2.2‰ (Chenery et al. 2012). For comparison, the $\delta^{18}O_{VSMOW}$ value for annual precipitation at Ibiza is estimated at ca. − 5.3 ± 1.5‰, a range that is widely shared along the eastern coast of Spain and the north coast of North Africa (http://waterisotopes.org; see also Araguas-Araguasa and Diaz Teijeiro 2005; Evans et al. 2012) and so is of limited resolution in terms of investigating an individual's origins. Taken at face value, only one individual at 33BVR (BVR155) is consistent with a local origin, with the others all being ^{18}O-depleted, raising the possibility of origins in the mountains of southeast (cf. Guede et al. 2017: Fig. 8) or northern Spain (cf. Prevedorou et al. 2010). A similarly high proportion of immigrants was also inferred from stable sulphur isotope ($\delta^{34}S$) data in a study by Nehlich et al. (2012), in which the authors concluded that 18 of 20 Islamic period individuals analysed from Es Soto were immigrants to Ibiza. This could perhaps be seen in the context of Eivissa's position as the major port of the island. But there are numerous complications with making direct comparisons between $\delta^{18}O$ in enamel and precipitation, leading many researchers to avoid this approach altogether (Bell et al. 2010; Pellegrini et al. 2016; Pollard et al. 2011). Alternatives, however, rely on the presence of larger datasets than we have at present for the region.

A comparison of the $\delta^{18}O_c$ and $\delta^{13}C_{ap}$ results offers another way forward. Interestingly, the two isotopes are strongly correlated ($r^2 = 0.844$, $p = 0.01$, df = 5) (Fig. 7), suggesting the possibility of varying childhood origins. Those enriched in both ^{18}O and ^{13}C (BVR155, BVR104) would be consistent

Fig. 7 Plot of $\delta^{18}O_c$ and $\delta^{13}C_{ap}$ results on human tooth enamel from 33BVR, showing a strong positive correlation between the two isotopes ($r^2 = 0.844$, $p = 0.01$, df = 5)

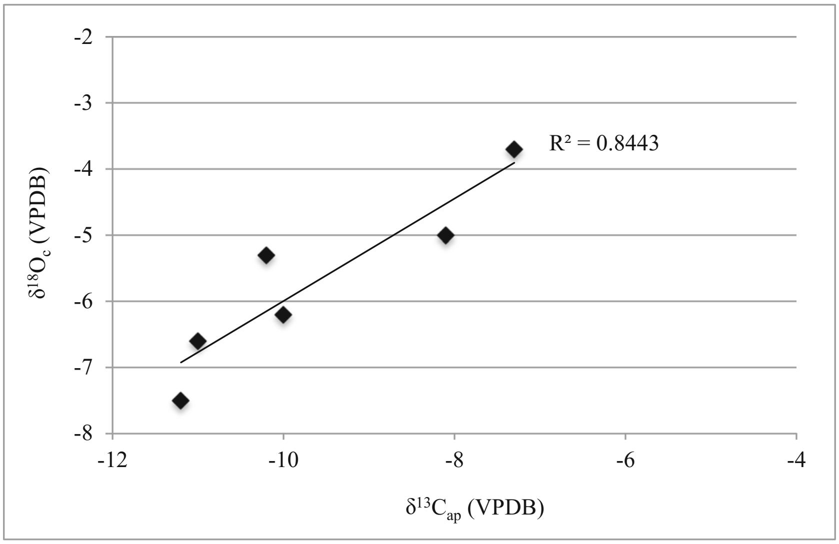


Table 6 Summary of human bone collagen data from 33BVR and sites in the surrounding region (excluding infants). For site locations see Fig. 1

Site	Date CE	Period	δ13C, $\bar{X}$ SD	δ15N, $\bar{X}$ ± SD	r^2	*p*	*n*	Reference
Sanisera, Minorca	4th–6th	Late Antiquity–Early Byzantine	− 18.3 ± 0.7	11.1 ± 1.2	0.267	0.040	16	Ziriax 2017
S'Hort des Llimoners, Ibiza	4th–6th	Late Antiquity–Early Byzantine	− 19.1 ± 0.4	10.9 ± 0.9	0.000	0.971	45	Fuller et al. 2010
33BVR, Ibiza	10th–12th	Medieval (Islamic)	− 18.6 ± 0.8	10.8 ± 0.5	0.198	0.006	37	this study
Es Soto, Ibiza	10th–13th	medieval (Islamic)	− 18.1 ± 1.3	10.9 ± 1.0	0.234	0.026	21	Fuller et al. 2010
Can Fonoll, Ibiza	10th–13th	Medieval (Islamic)	− 19.0 ± 1.3	10.3 ± 0.8	0.008	0.334	109	Pickard et al. 2017
El Raval, Valencia	14th–16th	Medieval (Islamic)	− 16.4 ± 0.6	12.1 ± 0.3	0.001	0.882	35	Salazar-García et al. 2014
Benipeixcar, Gandía, Valencia	15th–16th	Medieval (Islamic)	− 16.4 ± 0.9	10.7 ± 0.6	0.071	0.255	20	Alexander et al. 2015
Colegiata de Santa María, Gandía, Valencia	13th–16th	Medieval (Christian)	− 17.2 ± 1.0	10.2 ± 0.8	0.096	0.140	24	Alexander et al. 2015

with the greater consumption of C_4 foods in more arid environments, such as those of the arid coastal region of southeast Spain. Individual BVR155's second molar yielded a $\delta^{18}O_c$ value of − 3.7‰. While their $\delta^{13}C_{coll}$ value of − 18.9‰ is not significantly raised above the 33BVR site average, the $\delta^{13}C_{ap}$ result of − 7.3‰ is the highest of the six individuals sampled, suggesting a more substantial dietary contribution of C_4 foods in childhood, with the subsequent adoption of the Balearic Island diet being reflected in the bone collagen values.

Bartomeu Vicent Ramon in its temporal and regional context

One of the questions posed in this paper is the impact of Islamic religion, cultural preferences and agricultural practices on Balearic foodways. In order to address this, 33BVR needs to be seen in the context of what went before and what came after (Table 6; Fig. 8). In addition, there is the matter of whether or not diets differed on the islands versus the adjacent mainland, either because of easier access to marine foods, and/or because of the differing possibilities for farming and herding. A caveat when comparing isotopic data produced in various laboratories with varying sample preparation protocols and instrumentation is that they may be subject to small interlaboratory differences (Pestle et al. 2014). Any larger differences observed, however, should be robust, as should even small differences found within single studies.

The differences between Late Antiquity/Early Byzantine and the medieval Islamic period on the Balearic Islands are relatively minor for both isotopes and tend to be site-based rather than temporal: Can Fonoll, for example, stands out from the other sites in having significantly lower means for both isotopes ($p < 0.01$ in all comparisons, with the exception of no significant difference in $\delta^{13}C$ compared to S'Hort des

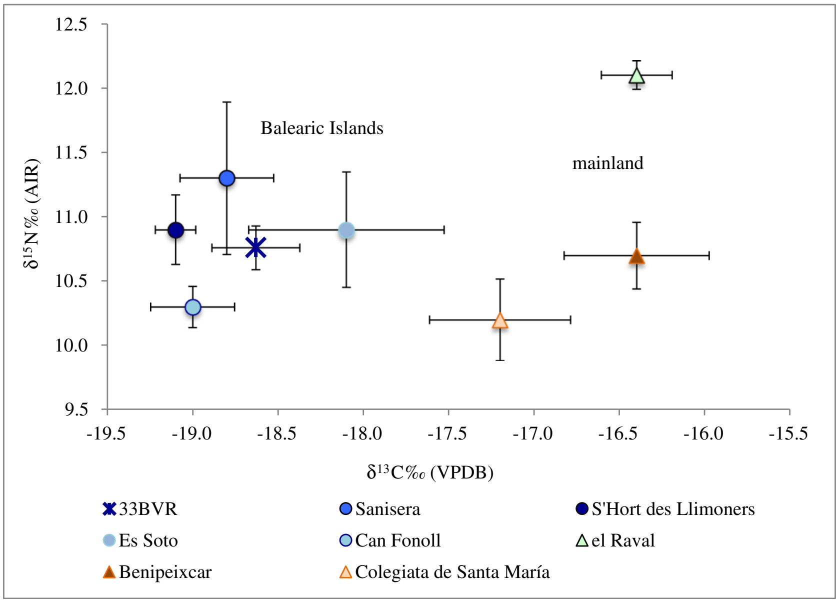


Fig. 8 Human $\delta^{13}C$ and $\delta^{15}N$ values ($\bar{X}$ ± 2SE) for comparative medieval and Islamic sites (infants excluded)

Llimoners). On the face of it, this would suggest that there was no marked increased emphasis on C_4 crops following the early tenth century Islamic colonisation of the Balearics. However, as discussed above, $\delta^{13}C$ measurements on collagen can underrepresent the contribution of lower protein plant foods, particularly when there is sufficient animal protein in the diet. To resolve this matter will require $\delta^{13}C_{ap}$ analysis of enamel from the earlier periods. There is a small but significant average decrease of ca. 0.5‰ in $\delta^{15}N$ between Late Antiquity/Early Byzantine (Sanisera and S′Hort des Llimoners, $n = 61$) and the Islamic period (33BVR, Es Soto and Can Fonoll, $n = 170$) on the Balearics (Mann-Whitney U test, $Z = 3.141$, $p = 0.002$), which could relate to a decline in the consumption of marine foods and/or animal products more generally, to an increase in the consumption of pulses or indeed to a combination of all three. This decrease in the medieval period can be taken as robust, since $\delta^{15}N$ values are on average also higher in the Punic period sites on Ibiza (Can Marines, Puig des Molins and Ses Païsses de Cala d'Hort), on par with those in Late Antiquity (Fuller et al. 2010; Salazar-García 2011).

The three medieval Islamic sites on Ibiza are broadly contemporary in the tenth to twelfth/thirteenth centuries and are all located in the southeast of the island. Indeed, Es Soto and 33BVR are both in Eivissa, while Can Fonoll is ca. 5 km to the southwest (Fig. 1). Despite their spatial and temporal proximity, the site means differ slightly but significantly in both $\delta^{13}C$ and $\delta^{15}N$ for all pairwise comparisons, with the exception of $\delta^{15}N$ between 33BVR and Es Soto (Table 7). The implication is one of very small-scale local differences in diets between contemporaneous populations. This is perhaps easiest to understand when comparing the rural site of Can Fonoll with the two Eivissa sites, with the latter having greater access to marine foods and to imported foodstuffs (Pickard et al. 2017), though it was not until the twelfth century that the Balearic Islands became more thoroughly enmeshed in international Mediterranean trade (Doxey 1994). The explanation for this subtle, small-scale patterning may instead relate to the strong, clan-based territorial divisions on Ibiza set out during its resettlement in 902 (Kirchner 2002, 2006, 2009; Kirchner and Retamero 2015: Fig. 4.7). A number of such territories ran radially through Eivissa and its hinterland, providing access to the port to different clans (Kirchner 2002: 173). It is possible that the various clans emphasised slightly different combinations of crops and animals in their diets, depending on the local soils and access to irrigation, differences in their labour pools and wealth etc. Further exploration of this idea would firstly need to confirm that the small isotopic differences observed are 'real' and not an artefact of inter-laboratory measurement variability (Pestle et al. 2014).

Table 7 Results of pairwise Mann-Whitney U tests for medieval Islamic sites on Ibiza. The critical p value for the rejection of the null hypothesis is 0.017, reflecting the Bonferroni correction for mulitple comparisons ($k = 3$)

Site	$\delta^{13}C$		$\delta^{15}N$	
	Z	p value	Z	p value
33BVR v. Es Soto	2.51	0.012	0.947	0.344
33BVR v. Can Fonoll	4.37	0.000	2.65	0.008
Es Soto v. Can Fonoll	5.30	0.000	2.67	0.008

Much stronger, and therefore more robust, differences are seen between the Balearic Islands and the adjacent mainland during the medieval period. The mainland sites of El Raval, Gandía-Benipeixcar and Gandía-Colegiata de Santa María are all significantly higher in $\delta^{13}C$, suggesting greater consumption of C_4 foods. The contribution of marine foods is made improbable for these sites, despite their coastal locations, by the absence of any positive correlations between $\delta^{13}C$ and $\delta^{15}N$ results (Table 5). This includes the late medieval Islamic site of El Raval (fourteenth to sixteenth centuries), which exhibits a significantly higher average $\delta^{15}N$ value than any of the other sites considered here, but shows no correlation with $\delta^{13}C$ values (Salazar-García et al. 2014). Gandía presents an interesting case, as both Islamic (Benipeixcar) and Christian (Colegiata de Santa María) communities were present during the late medieval period (thirteenth to sixteenth centuries), though Benipeixcar was a Muslim enclave on the outskirts of the larger town of Gandía (Alexander et al. 2015). Significantly higher $\delta^{13}C$ values from Benipeixcar suggest a greater contribution of C_4 foods for the Muslim *mudéjares* than for the Christian community at Colegiata. Interestingly, this difference appears to have been driven largely or entirely by enriched ^{13}C in Muslim females, with no clear differences seen between Muslim males and Christian males and females (Alexander et al. 2015: Fig. 4). While $\delta^{15}N$ values are on average significantly higher at Benipeixcar (10.7 ± 0.6‰) than at Colegiata (10.2 ± 0.8‰), the lack of any correlation with $\delta^{13}C$ values again provides no clear support for greater consumption of marine fish by either the Islamic or the Christian communities, despite expectations arising from religious prohibitions for the latter (Tomás 2009).

In contrast to the mainland, some sites on the Balearic Islands show low but statistically significant positive correlations between $\delta^{13}C$ and $\delta^{15}N$ (Table 5), consistent with some contribution of marine foods in island diets. The two exceptions are the Late Antiquity/Byzantine cemetery at S′Hort des Llimoners and the large Islamic cemetery of Can Fonoll, both on Ibiza (Fuller et al. 2010; Pickard et al. 2017). The site means at Can Fonoll of − 19.0 ± 1.3 and 10.3 ± 0.8‰ for $\delta^{13}C$ and $\delta^{15}N$ ($n = 112$), respectively, indicate predominantly C_3 diets. Five individuals are identified as outliers in $\delta^{13}C$, with values above − 18‰ (but no corresponding increase in $\delta^{15}N$), the highest being − 8.6‰, suggesting a diet almost entirely comprised of C_4 foods and so undoubtedly a recent migrant to Ibiza (Pickard et al. 2017). Removing these outliers, together with an infant, does result in a significant positive correlation between δ^{13}C and δ^{15}N values in the remaining 106 individuals, though it is very low and arguably not meaningful ($r^2 = 0.056$, $p = 0.014$, df = 105). It should be noted here that the suggestion in Pickard et al. (2017: 4) that Mediterranean fish have similar δ^{13}C and δ^{15}N values to terrestrial fauna, and so cannot be easily distinguished in isotopic studies, is, in the case of the former, based on an inappropriate comparison of modern fish flesh values to archaeological fish bone. Thus, for example, the average δ^{13}C value of − 17.8‰ in the cited study of modern fish off the coast of Ibiza (Polunin et al. 2001; cf. Garcia-Guixé et al. 2010) needs to be adjusted by + 2.9‰ for tissue fractionation (Robson et al. 2012), and by a further + 1.1‰ to account for ^{13}C-depletion of the modern atmosphere and oceans by the burning of fossil fuels, thus raising the expected analogous archaeological bone collagen value to − 13.8‰, entirely compatible with marine bone collagen measurements obtained along the Atlantic façade (cf. Schulting 2018; see also Alexander et al. 2015: Table 2). Stable nitrogen isotope values in the Mediterranean, however, are relatively low.

An issue when investigating the role of marine foods, as discussed above and as also noted by Pickard et al. (2017; cf. Craig et al. 2009), is that their contribution to δ^{13}C in bone collagen can be masked in diets dominated by C$_3$ carbohydrates (wheat, barley, rice) and lipids (e.g. olive oil). The fact that we see positive correlations at some sites suggests that it may still be possible to detect low-level consumption of marine foods in bulk stable isotope measurements of collagen. A question that arises, then, is whether similar levels of marine resource utilisation on mainland sites would be rendered isotopically invisible in terms of δ^{13}C by being swamped by the greater dietary contribution of C$_4$ plants there, which would have the effect of obscuring any correlation with δ^{15}N values. Nevertheless, based on the presently available evidence, the results from 33BVR suggest that marine foods constituted only a minor component to Balearic diets, consistent with the findings of previous isotopic studies (Davis 2002; Fuller et al. 2010; Nehlich et al. 2012; Pickard et al. 2017; Salazar-García 2011; Van Strydonck et al. 2002, 2005; Ziriax 2017).

The three mainland sites all exhibit a higher reliance on C$_4$ crops than the Balearic Islands, though the explanation for this is not yet clear. The sites differ in age, with those on the mainland all being late medieval (thirteenth/fourteenth to sixteenth centuries) while the Balearic sites are earlier (tenth to thirteenth centuries). The decrease in rainfall in the western Mediterranean during the Medieval Climatic Anomaly might be expected to favour millet and sorghum, both drought resistant and with short growing seasons, but this event dates to the eleventh to thirteenth centuries (Roberts et al. 2012), and so largely overlaps both the mainland and insular sites.

To return to the two questions posed at the beginning of this paper, we do not see any clear isotopic impacts following from the Islamic conquest on the Balearic Islands. It may be that this expectation was itself flawed, given that C$_4$ crops were present on the Iberian Peninsula since at least the Middle Bronze Age and would already have been integrated into the farming economy to some extent (Alonso 2008; Buxó and Piqué 2008). If anything, the greatly improved irrigation systems introduced into al-Andalus by Arab and Berber settlers (Kirchner 2002, 2006, 2009; Kirchner and Retamero 2015; Retamero 2008; Watson 1983) may have facilitated a greater emphasis on more highly culturally valued C$_3$ crops, especially wheat. The frequent focus in stable isotope studies on the contributions of C$_4$ (and marine) foods is driven in part by the analytical technique itself, since there is such a clear distinction between the ^{13}C values of C$_3$ and C$_4$ plants, ostensibly making this a very amenable research question. At the same time, it must be recognised that the analysis of δ^{13}C in bone collagen will be biased against C$_4$ crops when there is sufficient C$_3$-based animal protein in the diet. Of course, wheat, barley, rice and legumes are also C$_3$ crops, with the latter higher in protein than cereals, again acting against the detection of low to moderate C$_4$ consumption. That this can be partly overcome by the analysis of δ^{13}C$_{ap}$ in enamel carbonate has been suggested with the preliminary results presented here. This approach needs to be applied more widely, to determine the extent of and variability in the impact of C$_4$ crops across medieval Iberia.

Conclusions

The stable isotope and ^{14}C dating results presented here from the Islamic necropolis of 33 Bartomeu Vicent Ramon add to the growing body of data on diet and mobility on Ibiza and the Balearic Islands, as well as contributing to studies of the wider region. The bone collagen δ^{13}C and δ^{15}N results offer further support for the dominance of C$_3$ plant and animal foods, with a substantial contribution from C$_4$ crops and a minor contribution from marine resources both likely. That the contribution of C$_4$ foods may be underestimated more generally in medieval Spain is suggested by the enamel carbonate δ^{13}C data for six individuals, which to our knowledge represents the first such results for this region. Similar problems may arise in the underestimation of the use of marine foods, when consumed together with large amounts of carbohydrates and/or lipids from cereals and olive oil, respectively. Future research on these matters might make additional use of other isotopes (sulphur, hydrogen, strontium), single amino acid analysis and high-resolution sequential sampling of enamel and dentine in order to obtain more detailed life histories.

While not showing the presence of immigrants as clearly as some previous studies, the collagen δ^{13}C and the enamel δ^{18}O$_c$ and δ^{13}C$_{ap}$ results from 33BVR suggest the presence of both recent and earlier arrivals to the island from regions with a greater emphasis on C_4 foods. Based on previously published $\delta^{13}C$ results from the mainland around Valencia, and the historically attested origins of the Berber clans as coming primarily from al-Andalus, this region seems plausible as their source. While complications in the interpretation of $\delta^{18}O_c$ results were highlighted, specifically in terms of direct comparisons with $\delta^{18}O$ in meteoric waters, this avenue of investigation is promising. Despite the comparative homogeneity of precipitation values across much of the coastal western Mediterranean, the variation seen in even the limited number of individuals analysed here suggests that they originated from a number of different locations. This was further confirmed by the strong positive correlation seen with enamel $\delta^{13}C_{ap}$ values. The availability of larger datasets both from individual sites and from the wider region would facilitate an alternative approach focused directly on variability in the distribution of results, circumventing problems with comparing $\delta^{18}O$ values in enamel and in precipitation.

While the Balearic sites exhibit broadly similar $\delta^{13}C$ and $\delta^{15}N$ results, suggesting similar diets, there are some significant differences between roughly contemporaneous sites on Ibiza, between pre-Islamic and Islamic sites on Ibiza and between pre-Islamic sites on Minorca and Ibiza. What is less clear is the extent to which these are entirely site-based (or indeed lab-based differences in isotopic measurements) or whether there is a more consistent underlying temporal and/or spatial pattern. A clearer pattern does emerge in a comparison of medieval Islamic sites on Ibiza with those on the adjacent Andalusi mainland, where consistently greater use was made of C_4 crops. Why this should be so remains unclear, and could be the focus of a concerted multidisciplinary study combining isotopic approaches with specialists in the analysis of irrigation systems, medieval farming practices and the socio-political milieu of this dynamic period of Iberian history.

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