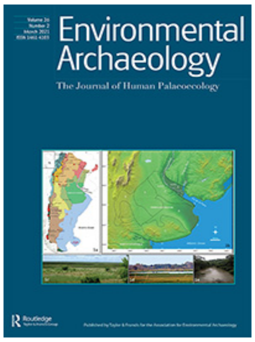

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Caprine Mobility on the Balearic Islands During the Middle and Late Bronze Age (ca. 1600–850 BC): First Results Based on Strontium Isotopes ($^{87}Sr/^{86}Sr$)

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ABSTRACT

This study presents the $^{87}Sr/^{86}Sr$ ratios from the tooth enamel of 57 sheep and goat specimens, in order to explore animal mobility in the Middle and Late Bronze Age society of the Balearic Islands (Naviform period). Seven archaeological sites from Mallorca and Menorca located in different biotopes and with different functionalities were selected. The results provide some of the first data on the geographic range of meat provisioning at each site. In addition, several present-day leaves, as well as tooth dentine and bones were analysed to assess local strontium isotopic ratios in different geological layers existing in the Balearic Islands. The results suggest that most caprines were sourced from the neighbouring areas of each site, but also suggest a correlation between strontium isotope variability and site function: domestic settlements and sites related with maritime exchanges had significantly more variability compared to fortified sites. In addition, the ritual cave of Cova del Camp del Bisbe had the highest diversity of strontium isotopic ratios, thus suggesting that caprines were brought here from a variety of different locations.

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Introduction

The study of mobility during Prehistory is important for our understanding of how people perceived and exploited the landscape they lived in, but also to increase knowledge about their social organisation and identity (i.e. Broodbank 1993; Knapp and Van Dommelen 2010). The analysis of space and mobility on islands can be a challenge because aspects related to naval technology or marine infrastructures and mobility must be considered (Calvo et al. 2011). For archaeology in the Balearic Islands, one of the main current research questions is to assess the degree of insular connectivity and mobility of animal and human populations during the Bronze Age.

The Bronze Age on the Balearic Islands is characterised by the Naviform culture, also called Pretalayotic or Dwelling Naveta (ca. 1600–850 BC; Lull et al. 1999; Calvo, Guerrero, and Salvà 2001; Guerrero et al. 2007; Calvo 2009; although some authors place the end of the Naviform period in the late 2nd millennium cal BC, see Ramis and Salas 2014; Gelabert, Hernández-Gasch, and Puig 2018) (see supplementary material S1). The settlements were open-air villages without walls, composed of a few stone-made houses of a horseshoe or inverted ship shape. According to bioarchaeological evidence, these societies had a mixed economy based on agriculture and animal husbandry, and no evidence of hunting or fishing has been found (e.g. Ramis 2006; Valenzuela-Suau 2020). During the Middle and Late Bronze Age, sheep and goats were the most represented taxa (Ramis 2006; Ramis and Anglada 2012; Valenzuela-Suau and Valenzuela-Lamas 2013; Valenzuela-Suau 2020) (see also supplementary material S2).

Although most sites were open-air settlements, the excavations at Sa Ferradura and Cala Morell revealed that they were closed by walls, and were located in inhospitable places to live (e.g. because of their exposure to strong wind). For these reasons, some researchers suggest that these sites could have been related to social instabilities: places where people could find refuge from conflicts in the interior of the islands (Anglada et al. 2017).

The available archaeological data show a certain degree of mobility because some materials that are naturally absent on the islands –such as ivory and tin– are found at Bronze Age sites (e.g. Delibes de Castro and Fernández-Miranda 1988; Lull et al. 1999; Guerrero 2006; Calvo 2009; Salvà and Javaloyas 2013; Escanilla, Valenzuela-Suau, and Palomar 2017). Moreover, the arrival of ivory to the centre of Mallorca suggests the existence of exchange networks linking the interior of the island and the coast (Escanilla, Valenzuela-Suau, and Palomar 2017; Valenzuela-Suau et al. 2017). In addition, a clear homogeneity of domestic architecture and material culture existed and has been interpreted as a common

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habitus and evidence that people and ideas flowed between islands (Albero et al. 2011). In this sense, some settlements located directly on the beach, on promontories or islets, were thought to be exchange points or sites related with maritime navigation (e.g. Salvà, Calvo, and Guerrero 2002; Guerrero 2006; Guerrero et al. 2007; Calvo et al. 2011). In contrast, there is no evidence of the introduction of wild species during this time period, and zooarchaeological data suggest a local animal husbandry management system (e.g. Ramis 2006; Valenzuela-Suau 2020).

The main goal of this study is to assess the degree of mobility or isolation of domestic animals in Mallorca and Menorca during the Bronze Age based on direct chemical evidence. Strontium isotope analyses ($^{87}Sr/^{86}Sr$ ratios) are now well-established for assessing whether animals were raised locally or in other geological areas, as they provide direct evidence of geological origin during the period of enamel mineralisation (e.g. Balasse et al. 2002; Evans et al. 2007; Bendrey, Hayes, and Palmer 2009; Viner et al. 2010; Minniti et al. 2014; Brönnimann et al. 2018; Madgwick et al. 2019). In order to explore the degree of livestock mobility and the possible arrival of domestic animals from overseas, strontium isotopic analyses were performed on 57 caprine teeth (sheep and goats) from seven Bronze Age sites of different functionalities from Mallorca and Menorca.

Materials and Methods

Strontium Isotope Analyses

The study focused on caprine teeth, as sheep and goats constitute the most abundant species in the zooarchaeological record of Bronze Age Mallorca and Menorca (e.g. Ramis 2006; Ramis and Anglada 2012; Valenzuela-Suau 2020; see also supplementary materials, S2). While it is true that overseas trade could focus on selected body parts not including the heads, the anatomical profiles at the sites analysed here indicate that all the anatomical parts were present without any apparent over or under representation of any anatomical element. Consequently, it is likely that, if animals were imported, they were brought in 'on the hoof' and their presence can therefore be detected by the isotope analysis of their teeth.

Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) vary depending on the age of each geological formation, the original rubidium content of the bedrock and the lithology of the rocks (Bentley 2006). In general, the older and more felsic a rock formation is, the higher the proportion of ^{87}Sr produced by in situ radioactive decay of ^{87}Rb will be (Faure and Mensing 2005). As strontium substitutes for calcium, strontium isotope ratios of skeletal tissues derive from the bioavailable strontium of the area where food was sourced (Comar, Russell, and Wasserman 1957; Toots and Voorhies 1965). Enamel bioapatite preserves the strontium isotope composition fixed during enamel mineralisation, thus providing direct evidence of geological origin. In contrast, bone and dentine are more susceptible to diagenetic alteration and their $^{87}Sr/^{86}Sr$ ratio progressively equilibrates with the one of the burial environment (e.g. Nelson et al. 1986; Budd et al. 2000; Price, Burton, and Bentley 2002; Lee-Thorp and Sponheimer 2003; Evans et al. 2007; Madgwick, Mulville, and Evans 2012). Whether equilibration is complete depends on the conditions of the burial environment and also on how different the original (biogenic) $^{87}Sr/^{86}Sr$ is from that of the burial soil; on the whole, however, untreated bone and dentine have proven to be reasonable proxies of the bioavailable strontium isotopic ratio present at the archaeological site (Nelson et al. 1986; Budd et al. 2000; Chiaradia, Gallay, and Todt 2003; see e.g. Viner et al. 2010; Minniti et al. 2014; Madgwick et al. 2019). Previous comprehensive studies characterising biogenic strontium isotopic ratios (e.g. Evans et al. 2010; Brönnimann et al. 2018) suggest that present-day leaves from trees with deep roots located in undisturbed forests offer reliable data to characterise bioavailable strontium isotopic data. In the present study, however, the lack of undisturbed vegetation at the archaeological sites prevented us from collecting reliable leaf samples. Consequently, in order to assess the local strontium isotopic signature of each archaeological site and surrounding areas we analysed ten samples from different origins: three tooth dentine samples, three bone samples recovered from the sites, and four modern tree leaves from the areas in Mallorca which are least affected by human settlement (Table 1, see locations in Figure 2).

In order to facilitate data comparison between sites and individuals, we preferentially selected lower third molars that were fully erupted and formed (closed roots, c. >18–24 months old); however, because of the small number of teeth available from some sites, it was necessary to also sample nine lower second molars, some of these from younger individuals (c. 12 months old according to wear stage, Table 2). To ensure that data were collected from different individuals, an effort was made to obtain samples from the same side at each location (i.e. lower right or left).

The sampling protocol consisted of cutting a transversal slice from the protoconid of each tooth (one per individual) using a dentist drill with a diamond cutter disc at *CSIC-Institució Milà i Fontanals* laboratory (Barcelona, Spain). Each enamel sample was first mechanically cleaned with a rotation drill to remove all the dirt, tartar and dentine. The archaeological material was then returned to the museums for its curation. All samples were collected just above the enamel root junction (c.1 mm) to facilitate the comparison between individuals. The samples thus

Table 1. Strontium isotopic ratios obtained on modern tree leaves and sheep dentine/bone from different geologic formations.

Sample	GMS coordinates	Era	Period	Epoch	Bedrock	Species	$^{87}Sr/^{86}Sr$	Error (2σ)
M112	39°26′59.0″N 3°13′50.1″E	Mesozoic	Triassic-Jurassic	Upper Triassic-Lower Jurassic	dolomitic breccias, dolomitic rocks and limestones	Pinus	0.709451	0.000012
M162	39°52′25.5″N 2°59′0.53″E	Cenozoic	Paleogene	Eocene-Oligocene	conglomerates, breccias, sandstones, lutites, limestones	Quercus ilex	0.708327	0.000007
M165	39°35′19.97″N 3°13′53″E	Cenozoic	Neogene	Miocene	conglomerates, breccias, sandstones, lutites, limestones, marls and limestones	Pinus	0.709096	0.000009
SHO	39°2852.54″N 3°15′42.26″E	Cenozoic	Neogene	Miocene	white marls, limestones and biocalcarenites	Olea europaea	0.709091	0.000005
IPO	39° 45′ 16″N 3° 11′17″E	Cenozoic	Quaternary	Holocene	conglomerates, sandstones, sandstones, silts and clays	Sheep dentine	0.709193	0.000006
SFO	39° 32′ 41″N 3° 21′01″E	Cenozoic	Neogene	Miocene	white marls, limestones and biocalcarenites	Sheep dentine	0.709287	0.000006
CG0	39° 25′ 09″N 3° 14′40″E	Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Sheep dentine	0.709179	0.0000011
CCBO	39° 38′ 57.76″N 2° 54′ 21.27″E	Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Sheep bone	0.708963	0.000009
CBLO	39° 58′ 04″N 3° 50′ 10″E	Cenozoic	Neogene	Miocene	marls, biocalcarenites and reef limestones	Sheep bone	0.709194	0.000004
CMO	40° 03′ 27″N 3° 52′ 58″E	Mesozoic	Triassic-Jurassic-Cretaceous	Upper Triassic-Lower Cretaceous	massive dolomitic rocks, limestones, marls	Sheep bone	0.709236	0.000003

reflect the final period of tooth mineralisation. Both archaeological and present-day samples were then further cleaned, chemically processed and analysed at *Géosciences Montpellier* laboratory (Université de Montpellier–CNRS, France) following standard procedures (Pin et al. 1994; see Valenzuela-Lamas et al. 2018 for details). Isotopic ratios were measured with a Neptune+ Thermo Scientific Multi-Collector Inductively-Coupled-Plasma Mass Spectrometer (MC-ICP-MS) from the AETE-ISO platform (OSU OREME) at the University of Montpellier. Total chemistry blanks were less than 20pg and thus negligible for this study. The samples were alternatively run with international NBS 987 standards using a sample-standard-bracketing measurement protocol wherein standards were run every 3 unknowns. The ^{88}Sr beam intensity for all standards and samples ranged from 8 V to 15 V. $^{87}Sr/^{86}Sr$ isotopic ratios were corrected for mass fractionation using an exponential mass bias law and a $^{86}Sr/^{88}Sr$ of 0.1194. Then the corrected isotopic ratios were normalised to the NBS 987 standards, which gave a mean value of 0.710247 with a reproducibility of ± 0.000003 (2s, $n = 12$) during the course of this study.

Study Sites

The geology of the Balearic Islands originated from the materials deposited during the Phanerozoic eon (Figure 1). In Mallorca there are three main different geological zones: Tramuntana, in the NW, formed by Palaeozoic and Mesozoic rocks where karst formations predominate, a Quaternary, mostly Pleistocene plain in the middle, and Migjorn, to the SE, formed by Tertiary (mostly Miocene) rocks (Price and Herman 1991). In Menorca, older materials from the late Primary era with siliceous rocks emerge in the northern part of the island, and bedrock is younger and calcareous in the southern part (Figure 2).

Seven archaeological sites –five from Mallorca and two from Menorca– with different functions and located in different environmental settings were selected based on levels of preservation and reliable dating evidence (Figure 2).

Els Closos de Can Gaià (Portocolom, Mallorca) (CG) is a Naviform village located on Holocene conglomerates, sandstones and gravels at 700 m inland from the southwest coast of Mallorca (Figure 2), where different houses (also called navetiforms) clustered around an open-air space (e.g. Calvo and Salvà 1999; Javaloyas, Fornés, and Salvà 2007). The zooarchaeological study suggests that animal production was focused on caprines through the Bronze Age occupation (c. 90% of the domestic triad; Valenzuela-Suau and Valenzuela-Lamas 2013; Valenzuela-Suau 2020). Five of the seven teeth selected for isotopic analysis were collected from the two occupation layers

Table 2. Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) obtained from archaeological sheep and goat enamel from seven archaeological sites from Mallorca and Menorca. In the table s/g refers to individuals that could not be identified at a specific level.

Sample code	SU	Tooth	Specie	Wear stage (Payne 1987)	87Sr/86Sr	± (2sigma)
CCB2	140	m3 inf	sheep	11G	0.708948	0.000005
CCB5	142	m3 inf	s/g	11G	0.709137	0.000004
CCB6	140	m3 inf	s/g	6G	0.708214	0.000009
CCB7	142	m3 inf	sheep	8G	0.708471	0.000005
CCB8	142	m2 inf	s/g	7G	0.708651	0.000008
CCB9	142	m3 inf	s/g	9G	0.708789	0.000004
CCB11	142	m3 inf	s/g	11G	0.708903	0.000004
CCB12	142	m3 inf	s/g	11G	0.70883	0.000005
CCB15	142	m2 inf	s/g	5A	0.708878	0.000011
CCB30	142	m3 inf	sheep	2A	0.708696	0.000027
CG1	18	m3 inf	sheep	11G	0.70883	0.000007
CG2	36	m3 inf	sheep	8G	0.709242	0.000004
CG3	86/89	m3 inf	s/g	5A	0.709051	0.000004
CG4	9	m3 inf	sheep	11G	0.709187	0.000006
CG5	36	m3 inf	sheep	11G	0.709137	0.000003
CG6	36	m2 inf	s/g	9A	0.709056	0.000005
CG8	9	m3 inf	s/g	11G	0.708934	0.000003
CM4	9	m2 inf	sheep	8A	0.709209	0.000003
CM6	2	m2 inf	sheep	9A	0.709255	0.000003
CM7	2	m3 inf	sheep	11G	0.709262	0.000003
IP3	112	m2 inf	s/g	8A	0.708736	0.000005
IP4	112	m3 inf	sheep	6G	0.709132	0.000005
IP5-1	132	m3 inf	sheep	8G	0.70874	0.000004
IP6	132	m2 inf	sheep	7A	0.708998	0.000003
IP11	112	m2 inf	s/g	8A	0.708684	0.000003
IP12-1	112	m3 inf	sheep	7G	0.709154	0.000003
IP13-1	112	m3 inf	sheep	10G	0.709143	0.000003
IP14	139	m2 inf	sheep	5A	0.708756	0.000003
IP15	139	m2 inf	sheep	5A	0.708737	0.000007
IP16	139	m3 inf	sheep	7G	0.70916	0.000005
IP17-1	139	m3 inf	sheep	11G	0.70914	0.000003
IP21-1	9	m3 inf	sheep	4A	0.708634	0.000004
IP24	9	m3 inf	sheep	11G	0.708604	0.000004
IP26-1	9	m3 inf	sheep	10G	0.70919	0.000003
SF1	7	m3 inf	sheep	17G	0.709369	0.000003
SF4	7	m3 inf	sheep	2A	0.709549	0.000004
SF5	7	m3 inf	sheep	11G	0.709447	0.000004
SF6	18	m1 inf	sheep	5A	0.709461	0.000004
SF7	18	m3 inf	sheep	11G	0.709431	0.000005
SF9	18	m3 inf	sheep	11G	0.709476	0.000004
SF10	7	m2 inf	sheep	8A	0.709573	0.000003
SF14	18	m2 inf	sheep	7A	0.709384	0.000003
SH1	23	m3 sup	sheep	11G	0.709256	0.000006
SH4	23	m2 inf	sheep	7A	0.708769	0.000007
SH5	7	m3 inf	sheep	2A	0.708918	0.000003
SH16	50	m2 inf	s/g	7A	0.709289	0.000004
SH17	66	m3 inf	sheep	5A	0.709368	0.000007
SH19	67	m3 inf	sheep	5A	0.709277	0.000004

CBL1	86/961	m3 inf	sheep	11G	0.709548	0.000007
CBL3	86/266	m3 inf	sheep	11G	0.709191	0.000003
CBL4	86/935	m3 inf	sheep	11G	0.709321	0.000006
CBL7	86/374	m3 inf	sheep	8G	0.709521	0.000007
CBL11	86/131	m3 inf	sheep	11G	0.709526	0.000006
CBL12	86/472	m3 inf	sheep	6G	0.709349	0.000007
CBL14	86/602	m3 inf	sheep	5A	0.709247	0.000007
CBL16	86/61	m3 inf	sheep	11G	0.709111	0.000006
CBL18	86/998	m3 inf	sheep	5A	0.709401	0.000009

of the navetiform 1 house – and another two (CG1 and CG3) were collected from structure IIA (Javaloyas et al. 2011, 2013; Oliver 2005).

S'Hospitalet Vell (Manacor, Mallorca) (SH) is an open-air Bronze Age village located on Miocene white marls, limestones and biocalcarenites near the coast, not far from Els Closos de Can Gaià (Figure 2). It probably had a long-term occupation from ca. 1500–900 cal BC (Ramis and Salas 2014) and included Iron Age layers – not analysed here. The six teeth selected from Bronze Age layers originate from navetiforms 3 and 4.

Sa Ferradura (Porto Cristo, Mallorca) (SF) is located on a rocky promontory in the same geological bedrock as S'Hospitalet Vell (Figure 2). The site is only accessible through an isthmus and it was fortified with a wall (Anglada et al. 2013, 2015). No house structures have been recovered and the occupation was probably short, ca. 1100–900 cal BC (Anglada et al. 2017). Nevertheless, the domestic activities attested suggest that it may have been used as a non-permanent refuge (Anglada et al. 2013, 2017). The underlying geology is the same as S'Hospitalet Vell (Miocene white marls, limestones and biocalcarenites; Figure 2). The zooarchaeological study (Ramis 2018) showed that sheep and goats were the most represented taxa. All seven samples were collected from a large open-air area with several hearths (Sector I).

S'Illot des Porros (Sta. Margalida, Mallorca) (IP) is a small islet on the north coast of the Alcudia Bay formed with Holocene materials (Figure 2). Several non-domestic structures were erected during the Naviform period (Hernández et al. 1998). The functionality of the site is not clear, but it could have been related to maritime navigation, maybe as a trading place (e.g. Guerrero 2006; Guerrero et al. 2007; Calvo et al. 2011). Fourteen teeth were selected from two different Naviform phases. The faunal study (Valenzuela-Suau 2020) indicates that sheep were the most represented taxa at the site during the Bronze Age.

Cova del Camp del Bisbe (Sencelles, Mallorca) (CCB) is located at the centre of Mallorca, on a geological layer formed by Pliocene lutites, marls, calcarenites, sands and conglomerates. Although the C14 results confirm its use as a funerary cave during the Second Iron Age (ca. 450–250 cal BC), human bones from stratigraphically older layers did not have sufficient collagen preservation for radiocarbon dating and it is therefore not clear when this practice started (Palomar and Valenzuela-Suau 2018). However, the archaeological record shows that during the Bronze Age (ca. 1400–1200 cal BC), people consumed and deposited a huge volume of materials (cereals, ivory, ceramic and faunal remains, radiocarbon dated between 1400 and 1200 cal. BC, see supplementary

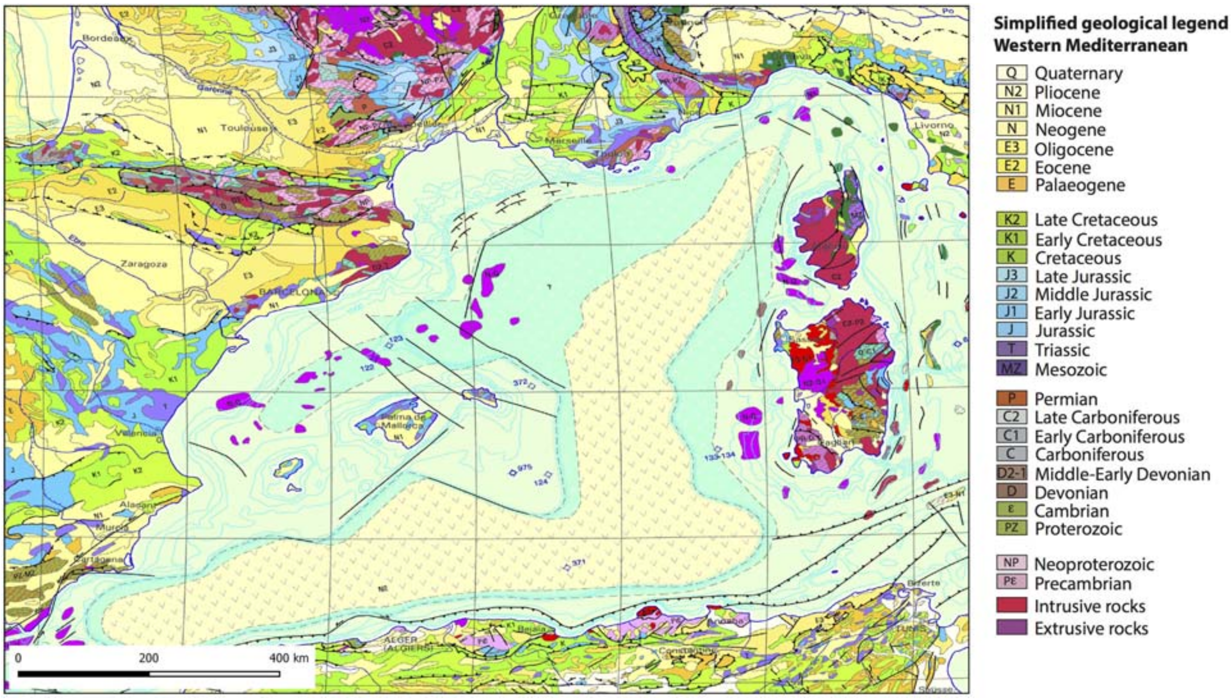

Figure 1. Geological bedrocks present in the Western Mediterranean. Data source: BGR.

material S1) (Valenzuela-Suau et al. 2017; Palomar and Valenzuela-Suau 2018). Other finds, including intentionally broken pottery and anatomically selected parts of sheep and pigs, found within a small concealed cavity (Valenzuela-Suau 2020), suggest several ritual actions in the cave during the Bronze Age. Ivory was recovered from Bronze Age layers, thus suggesting contacts between the coast and people inland (Escanilla, Valenzuela-Suau, and Palomar 2017; Valenzuela-Suau et al. 2017). The faunal record (Valenzuela-Suau et al. 2017; Valenzuela-Suau 2020) shows the predominance of sheep remains. All the teeth for strontium isotope analyses ($n = 10$) were selected from Bronze Age layers.

Es Coll de Cala Morell (Ciutadella, Menorca) (CM) is a Naviform village located on the top of a rocky promontory formed by Upper Triassic- Lower Cretaceous dolomites masses and limestones on the north-east of Menorca, 35 metres above the present-day sea (Figure 2). In this village, thirteen navetiforms and remains of domestic activities have been recovered, but some characteristics make it an unusual village, most notably because of the distribution of the houses and the wall that partly surrounds the village. Although it is an inhospitable place to live, it is thought that this site had a permanent occupation between ca. 1600/1500 cal BC and ca. 1200 cal BC (Anglada et al. 2015, 2017). Good sample collection

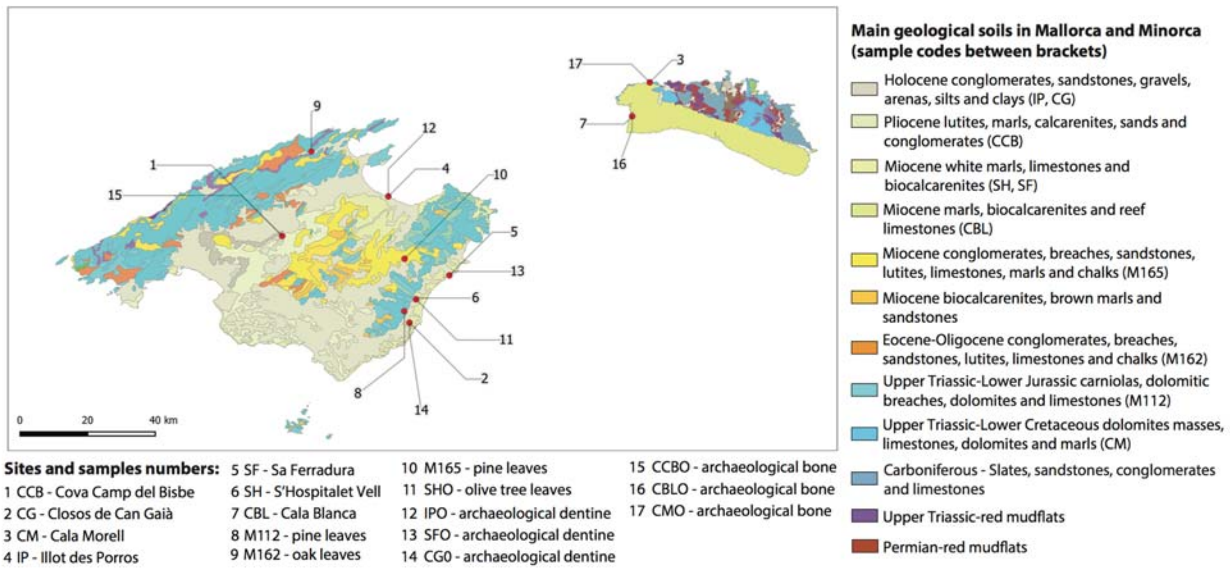

Figure 2. Location of the seven archaeological sites and modern samples from Mallorca and Menorca (right). Data source: IGME.

was difficult, and we could only analyse three teeth, all originating from an abandoned level of navetiform 11.

Cala Blanca (Ciutadella, Menorca) (CBL) is located on the present-day beach of Ciutadella, on the west coast of Menorca, on Miocene marls, biocalcarenites and reef limestones (Figure 2). This building is the first manifestation of cyclopean domestic architecture in the Balearic Islands, a navetiform (also called *naveta*) with an elongated structure with a southern orientation entrance, opposite to the apse. Evidence of only one structure wasuncovered during excavations. Even though the orientation of its entrance is different compared to other navetiforms and the apsidal part was not preserved, this structure is thought to be a navetiform (Juan and Plantalamor 1997) or a coastal navigation place (e.g. Guerrero 2006; Guerrero et al. 2007). The ^{14}C data gave an interval of use of ca. 1740–1250 cal. BC (Plantalamor and Van Strydonck 1997). The faunal study suggests that livestock was composed of sheep and goats, pigs and cattle (Ramis and Anglada 2012). Nine sheep teeth were selected, all coming from the same archaeological layer.

Results

Reference Samples

Table 1 shows the strontium isotopic ratios obtained from ten baseline samples (four modern leaf samples, three archaeological dentine and three archaeological bone samples). The results suggest that the sites and their surroundings have strontium isotopic ratios ranging from c. 0.7083–0.7095 (Table 1). These results are consistent with other studies analysing similar bedrocks in Mallorca and nearby Catalonia (e.g. Valenzuela-Oliver et al. 2016; Valenzuela-Lamas et al. 2018), as well as other comprehensive studies analysing Miocene, Triassic and Jurassic bedrocks from inland Europe (e.g. Brönnimann et al. 2018; Willmes et al. 2018; Bataille et al. 2020). All these works consistently indicate a range between 0.7080 and 0.7100 for the bedrocks present in Mallorca and Menorca. In addition, as a coastal region, seawater, rainfall and sea spray may contribute to ^{87}Sr/^{86}Sr isotopic ratios that are close to that of seawater (0.7092) (Bentley 2006).

Archaeological Samples

Table 2 shows the strontium isotopic results of the 57 Bronze Age caprine teeth from Mallorca and Menorca together with details about each tooth analysed, including the degree of species identification and wear stage. All archaeological enamel samples gave ^{87}Sr/^{86}Sr ratios between 0.7082 and 0.7095. These are remarkably consistent with the strontium isotopic variation obtained on the reference samples from Mallorca from different geologies (0.7083–0.7095, Table 1). Figure 3 displays the strontium isotope ratios in a more visual way.

The site with the widest range of strontium isotopic ratios (see Table 3) is the ritual cave of Cova de Camp del Bisbe (CCB), followed by the open habitat site of S'Hospitalet Vell (SH), the close-by port-of-trade of Illot des Porros (IP) and the open habitat sites of Closos de Can Gaià (CG) and Cala Blanca (CBL). The fortified sites – Sa Ferradura (SF) and Cala Morell (CM) – display the smallest ranges of strontium isotopic ratios (Table 3). Despite the limited number of samples from some sites, significant differences were found for the dispersion (variability) of the Sr isotope values between fortified and open air sites. First, the robust Brown-Forsythe Levene-type test based on the absolute deviations from the median (Brown and Forsythe 1974) confirmed that there are significant differences between sites (statistic = 2.6617; *p* value = 0.02554; see supplementary material S4). Second, a post-hoc Tukey's range test on the median absolute deviation (Tukey 1949) grouped by site type (ritual, open, and fortified) confirmed that fortified sites present significantly lower strontium variability than open air sites (*p*-value = 0.0138254, see supplementary material S4).

These differences in the variability of strontium isotopic ratios do not appear to be related to the location of each site (e.g. coast vs. interior) or the geological variability around them, but correlate with site functionality (most notably fortified vs. open air sites). Indeed some sites with low geological variability around them (e.g. Cala Blanca, S'Illot des Porros, see Figure 2) display higher diversity of strontium isotopic ratios compared with other sites whose surroundings are more geologically variable (e.g. Sa Ferradura, see also Cala Morell although only three samples are available from this site, see Figure 2).

Discussion

Ten samples of modern vegetation and archaeological bone and dentine from different geological formations were analysed to give a first insight into the bioavailable ^{87}Sr/^{86}Sr ratios present on different geological substrates in Mallorca and Menorca. This provided some reference values in addition to the two published in a previous study (Valenzuela-Oliver et al. 2016). The biosphere samples are all between 0.7083 and 0.7095 (Table 1) and therefore within the range obtained on similar geological substrates from continental Europe (~0.7080–0.7100. e.g. Brönnimann et al. 2018; Valenzuela-Lamas et al. 2018; Willmes et al. 2018; Bataille et al. 2020).

The strontium isotope values of the 57 archaeological enamel samples all fall between 0.7082 and 0.7095 (Table 2). This range is quite similar to those obtained

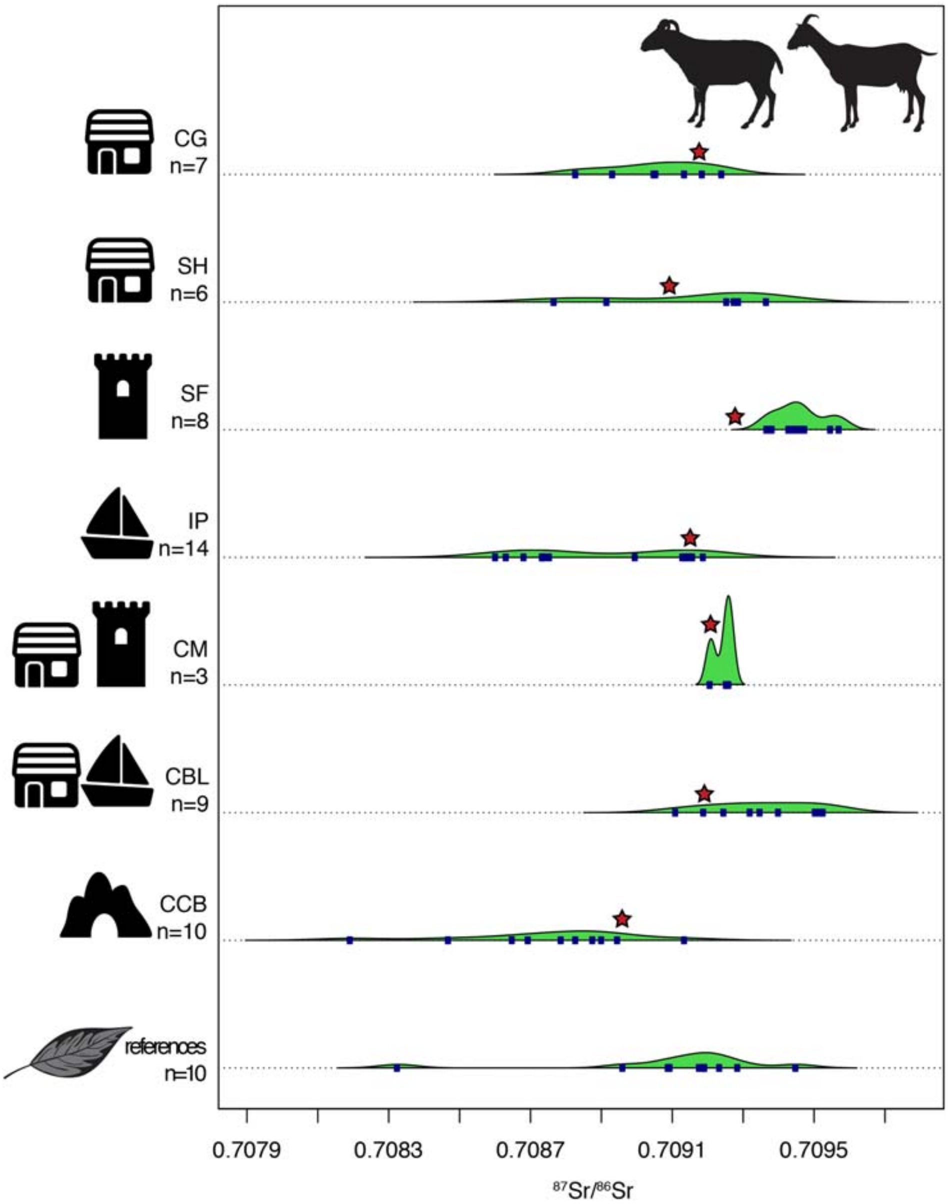

Figure 3. Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) recorded at each archaeological site (squares) and resulting density distributions. The star indicates the strontium isotopic ratio obtained from the reference sample at each site. Site abbreviations follow the ones at Figure 2 and the text. Icons refer to habitation sites (house), fortified sites (tower), trade sites (ship), sites with combined functions, cave.

from the biosphere samples expected for the bedrocks present in Mallorca and Menorca (0.7080–0.7100). Consequently, local rearing of sheep and goats, possibly including exchanges within the islands seems most plausible. There is no evidence for the import of caprines from locations with different lithologies, like the northern coast of Barcelona, the Pyrenean high mountain and other Western Mediterranean islands such as Corsica and eastern Sardinia. These would probably result in $^{87}Sr/^{86}Sr$ ratios be above 0.710, which is outside of the range of the values obtained for the samples studied. Nevertheless, the arrival of sheep and goats from other locations with similar geological characteristics and therefore similar $^{87}Sr/^{86}Sr$ isotopic ratios cannot be excluded. These areas include the eastern shore of the Iberian Peninsula, or some localities in southern France or North Africa, among others (Figure 1).

Interestingly, variability of strontium isotope ratios does not seem to be related to the presence of varied geological formations in the vicinity of each archaeological site but rather to site type, although it is acknowledged that some lithologies may produce more variable $^{87}Sr/^{86}Sr$ than others (Table 3). Nevertheless, the domestic settlement sites (i.e. Closos de Can Gaià (CG) and S'Hospitalet Vell (SH)) together with the sites related to maritime trade (Illot des Porros (IP) and Cala Blanca (CBL); Guerrero 2006; Calvo 2009) display a higher variability of strontium isotope ratios compared with the two fortified sites analysed (Sa Ferradura (SF) and Cala Morell (CM)), even if the various facies of geological terrains around the

Table 3. Maximum and minimum values of strontium isotopic ratios ($^{87}Sr/^{86}Sr$) from archaeological sheep and goat enamel at each site.

Site name	Site code	87Sr/86Sr min value	87Sr/86Sr max value	Mean	Standard deviation	Median absolute deviation	n teeth analysed	Functionality
Cova Camp del Bisbe	CCB	0.708214	0.709137	0.708752	0.000261	0.000126	10	ritual (funerary?)
S'Hospitalet Vell	SH	0.708769	0.709368	0.709146	0.000242	0.000062	6	open air navetiform village
Illot des Porros	IP	0.708604	0.70919	0.708915	0.000232	0.000249	14	site related with maritime navigation?
Cala Blanca	CBL	0.709111	0.709548	0.709357	0.000156	0.000158	9	navetiform/ site related with navigation?
Closos de Can Gaià	CG	0.708830	0.709242	0.709062	0.000144	0.000122	7	open air navetiform village
Sa Ferradura	SF	0.709369	0.709573	0.709461	0.000072	0.000047	8	fortified coastal head
Cala Morell	CM	0.709209	0.709262	0.709242	0.000029	0.000007	3	fortified coastal head/ navetiform village

latter are more diverse (see Figure 2 and Table 3, and supplementary material S3). Significantly, Sa Ferradura (SF) shows very homogeneous strontium isotopic ratios although they are all slightly higher than the biosphere value for the site (0.7093; see Figure 3). Whilst it is unlikely that the single biosphere sample from the site captures the whole variability around the location, this is at least not inconsistent with an occasional, possibly seasonal, use of the site, as has been suggested by previous researchers based on the geographical location and architecture (Anglada et al. 2013, 2015, 2017). Conversely, the ritual cave of CCB has the widest range of strontium isotopic ratios, thus suggesting that sheep and goats were brought from different places. Given its location in the centre of Mallorca (Figure 2) and its ritual use, the results may reflect different scenarios: if we assume that this site was used just by local people (from a village nearby), it is possible that these results reflect the contact and exchanges taken place between these local people and other communities on the island and overseas, as the wide variety of objects recovered from the cave –including ivory buttons– suggests (Escanilla, Valenzuela-Suau, and Palomar 2017; Valenzuela-Suau et al. 2017). In addition, it could also be that the cave was a significant place for several communities from the island who brought their animals and objects from different places.

Conclusions

This is the most comprehensive strontium isotopic study yet for the Balearic Islands in the Bronze Age. The objective of the study was to contribute with direct data to the understanding of the grazing strategies, animal and, by implication, human mobility during the Naviform period (1600–850 BC). For this purpose, a systematic sampling strategy was carried out in order to cover a number of biospheres (the two major islands, coastal and interior ranges), site types (ritual, habitat, fortified coastal headlands, ports-of-trade) and individuals from the most represented taxa (57 caprine teeth). Moreover, ten biosphere samples (modern tree leaves and archaeological dentine and bones) were analysed in order to characterise different geologies from Mallorca and Menorca. The results were consistent with those from corresponding lithologies from continental Europe and can be used for comparison in future studies.

The strontium isotopic ratios ($^{87}Sr/^{86}Sr$) obtained, albeit limited in number, suggest that there were differences between sites, probably related to their function (Figure 3, Table 3). The two sites located on fortified coastal headlands – Sa Ferradura (SF) in Mallorca and Es Coll de Cala Morell (CM) on Menorca – displayed the most local and restricted strontium isotopic variability, while the two open-air and long-term navetiform villages – Closos de Can Gaià (CG) and S'Hospitalet Vell (SH), both in Mallorca – together with the sites related with maritime navigation – Cala Blanca (CB) on Menorca and S'Illot des Porros (IP) on Mallorca – show higher diversity, thus suggesting that inhabitants exploited their nearby territory and may have had fluent exchanges with other settlements. The site displaying the widest strontium isotope variation is the ritual cave of Camp del Bisbe (CCB), located at the centre of the island. This suggests that exchanges occurred between different communities within the island and probably overseas (as indicated by the presence of ivory buttons; Escanilla, Valenzuela-Suau, and Palomar 2017; Valenzuela-Suau et al. 2017), and may also reflect that the cave was a significant place for several communities. Further biosphere samples are now needed in order to better understand the strontium isotopic variability at different locations and verify these results.

Despite the limitations imposed by the low number of samples at some sites and the need of further present-day samples from the Balearic Islands and beyond, the results provided here are a significant starting point for future research. This pilot study highlights the relevance of strontium isotopic studies for our understanding of mobility patterns in the past in combination with other archaeological data.

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