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Herd management and animal catchment areas at the *taula* enclosure of Binissafullet site (Menorca, Spain): A multi-isotopic approach[☆]

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ABSTRACT

This study presents the first isotopic analysis of livestock from a *taula* sanctuary dating from the Second Iron Age (c. 550-123 BCE) in Menorca (Spain). These emblematic structures contain the remains of animals, evidence of wine consumption, and other artefacts. Consequently, these structures are interpreted as sanctuaries or places where social cohesion was reinforced. The archaeological record reveals a blend of local and extra-insular elements. The main objectives of this study were to determine where the livestock buried within the taula enclosure were sourced from and to gain insight into how these communities exploited the available resources. To this end, the strontium ($^{87}Sr/^{86}Sr$), carbon ($\delta^{13}C$), and oxygen ($\delta^{18}O$) isotope ratios were analyzed in enamel samples taken from 27 domestic caprines found in the taula enclosure at Binissafullet site (Sant Lluís, Menorca). The results are mainly compatible with a livestock that grazed in the vicinity of the settlement and consumed C_3 type plants. This is consistent with the available palaeobotanical information, which shows a landscape characterized by Mediterranean vegetation with no C_4 plants present. Finally, some individuals are recorded as having grazed in more radiogenic areas, which were probably located in the northern part of Menorca (Tramuntana region, approximately 8 km from the settlement). This type of grazing has previously been documented in the Bronze Age on the island, and the results obtained here seem to suggest continuity in mobility-related livestock.

1. Introduction

The Late Iron Age in the Balearic Islands (c. 550-123 BCE) was characterized by social complexity, as evidenced by the region's architecture and material culture (Lull et al. 1999; Guerrero, 2006; 2007a). During this period, the indigenous people of the Gymnesian Islands (Mallorca and Menorca) underwent a period of socio-economic evolution that had coexist with the colony of *Ebusus* in the neighbour island of *Eivissa* (Calvo, 2009; Prados et al. 2015; Pons et al., 2020). This new political and economic situation clearly impacted in the local communities, as evidenced by the introduction of new products (e.g. wine) and beliefs (e.g. represented by the presence of foreign goddesses in local sanctuaries). However, there is no evidence of a military occupation of these major islands (Calvo, 2009; Pons et al., 2020; Riudavets and Ferrer, 2022). Differences between Mallorca and Menorca emerged during the preceeding Early Iron Age period (c. 850-550 BCE), as are shown by an earlier construction of tower-like buildings –known as *talaiots*- in Menorca and its monumentality (e.g. Curnia Nou site) (Anglada et al. 2019). However, it was during the Late Iron Age that clear architectural differences emerged between Mallorca and Menorca, such as the construction of domestic *cercles*-type structures or *taula* enclosures in Menorca from the 4th century BCE. These have been interpreted as

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reflecting the social complexity and evolution of this society (Gornés, 2022).

During the Prehistory, the Balearic Islands appear to have had a Mediterranean climate like that today, with no rivers (Piqué et al., 2002; Picornell-Gelabert, 2012; Picornell Gelabert et al., 2012; Pérez-Jordá et al., 2018). The landscape was characterized by the presence of trees, shrubs, and herbs that are typical of these climatic conditions (e.g. *Olea europaea sylvestris*, *Quercus ilex, Pinus halepensis, Pistacia lentiscus, and Erica* sp.) (Burjachs et al. 1994; 2016; Yll et al., 1997; Picornell-Gelabert, 2012; Portillo et al. 2014; Pérez-Jordà et al., 2018; Valenzuela-Suau et al. 2018; Servera-Vives and Riera, 2024). In general, from the arrival of human populations to the islands until the Late Iron Age, the Balearic economy was based on agriculture and animal husbandry with no major innovations. However, while general continuities are evident throughout this period, the construction of defensive walls and the presence of weapons in burial sites suggests that the transition to the Late Iron Age was not peaceful (Guerrero et al., 2007b; Moreno, 2012; Prados and Jiménez, 2017; Riudavets and Ferrer, 2022).

The agropastoral economy was based on the exploitation of animal and plant species adapted to the climatic and available resources. During the Late Iron Age, agriculture was focused on cereals such as barley and wheat (Pérez-Jordà et al. 2018). Interestingly, emmer wheat (*Triticum dicocum*) appears to have disappeared during this period, which could reflect an adaptation to poor soil quality (Pérez-Jordà et al. 2018). There is no evidence of the cultivation of fruit trees, such as the fig or olive, and oil production may have relied on mastic (*Pistacia lentiscus*) (Pérez-Jordà et al. 2018; Diodorus Siculus, V, 17). There is no evidence of the cultivation of foreign species such as almonds or pomegranates, or other species such as common millet, which is attested on the island of Eivissa during 7th-6th century BCE (Sureda et al., 2017; Pérez-Jordá et al., 2018).

In the Balearic Islands, the livestock economy focused on the domestic triad throughout prehistory, with domestic sheep and goats being more prevalent than cattle and pigs (Ramis, 2005; Ramis and Anglada, 2012; Valenzuela-Suau and Valenzuela-Lamas, 2013; Valenzuela-Suau et al. 2022a; Valenzuela et al., 2017; Valenzuela-Suau et al. 2018). Until the Early Iron Age period, and practically until the Late Iron Age, there is no evidence of the introduction of wild species, and hunting activities would have been merely residual or absent (Ramis, 2017; Marlasca, 2008; Valenzuela-Suau et al. 2022a; Valenzuela et al., 2017). During the Late Iron Age period, there was a change in the pattern of animal slaughter which, together with the discovery of possible cheese makers and looms, would indicate a greater preference for the use of secondary products such as cheese or wool compared to the previous phase (Morales, 2005; Ramis, 2017; Anglada et al. 2017; Riudavets and Ferrer, 2022). At the same time, there is evidence of the introduction of new species such as horses (*Equus caballus*) and rabbits (*Oryctolagus cuniculus*), which, together with the recovery of fish scales and large fishing hooks, would indicate a change in resource management during the Late Iron Age period. Nevertheless, their relative importance compared to the domestic triad would remain minimal (Anglada et al. 2017; Juan and Pons, 2005; Sintes and Isbert, 2009). The limited use of natural coastal resources during the Late Iron Age period would be corroborated by the scarcity of plants of this type in archaeological records, such as *Juniperus phoenicea* (Picornell-Gelabert, 2012; Anglada et al. 2017; Riudavets and Ferrer, 2022).

During this period, the number of settlements in Menorca increased from 241 in the Early Iron Age to 449 in the Late Iron Age (De Cet et al. 2017). Thus, a demographic growth must have occurred, possibly putting pressure on the land and between settlements (Riudavets and Ferrer, 2022). It seems that the older settlements maintain bigger measurements and could become principal centres, while the newer ones tended to be smaller. In Menorca, there is a clear division between the northern part, the so-called Tramuntana region, which contains the older geological units of the island (Paleozoic-Mesozoic), and the southern part, known as Migjorn, which is composed of Cenozoic units (see Figs. 1 and 2). Most of the villages were located on the *Migjorn* part of Menorca, in the southern part of the island (De Cet et al. 2013; Gornés et al. 2004). Considering the size of Menorca Island (702 km^2) and the theoretical exploitation zone of each settlement (approximately 5 km), it has been suggested that the agropastoral useful land of different settlements would have overlapped (De Cet et al. 2013; Riudavets and Ferrer, 2022) (Fig. 2). It is important to note that this would be reduced to less than 4 km^2 per settlement in the south-west part of the island (Riudavets and Ferrer, 2022). This scenario could explain archaeological findings indicating deforestation and human impact on the environment, such as the presence of herbaceous formations of nitrophilous-ruderal character at the Curnia Nou site, which are probably linked to herding activities (Portillo et al. 2014).

In this context of social complexity and new forms of relationships between settlements, the construction of enclosure structures emerged in Menorca from the 4th century BCE (Gual and Plantalamor, 1995; Fernández Miranda, 2009; Gornés et al. 2004; Gornés, 2022). These structures served to reinforce the hierarchy and socio-economic organization (Riudavets and Ferrer, 2022). These constructions are one of the most emblematic monuments of the island's prehistory. They consist of large stone structures in the shape of T located at the centre of ceremonial structures known as *taula* sanctuaries or *taula* enclosures (Plantalamor Massanet, 1991; Gornés, 2022). The ground plan is generally horseshoe-shaped or apsidal, with walls built using cyclopean masonry. The *taula* is in the centre of the space and is composed by a big vertical slab topped by an inverted and trapezoidal, often exceeding five metres in height (Fig. 2). Inside, semicircular chapels, stone platforms, benches, altars and combustion structures have been recorded (Gornés, 2022).

Inside the *taula* enclosures, a combination of local and off-island objects has been found such as pottery of various origins (e.g. Iberian, Ebusitan, grey Emporian) (Guerrero et al., 2007) together with bronze statuettes (e.g. the Egyptian Imhotep figure in Torre den Galmés site) (Fernández-Miranda, 2009). The presence of these foreign artefacts alongside local ones could reflect the existence of trade networks connecting Menorca with other Mediterranean cultures. However, the role of the indigenous population in these networks remains unclear (e.g. Ramon, 2017). Animal remains and pottery related to wine consumption have also being found, leading to the interpretation of these spaces as ceremonial centres of social cohesion or sanctuaries (Gual and Plantalamor, 1997; Gornés, 2022; Riudavets and Ferrer, 2022; Riudavets et al. 2023). Nevertheless, the meaning of these monuments is only partially understood, and little zooarchaeological data has been published (see e.g. Ferrer et al. 2020; Gornés, 2022; Riudavets et al. 2023).

This study aims to investigate how the Late Iron Age communities in Menorca perceived and managed their environment, and the extent to which they were culturally connected with other Mediterranean regions. Specifically, the study focused on: (1) characterizing the mobility of animals sacrificed in the taula enclosure to determine whether they were raised locally or transported from elsewhere; (2) gaining a better understanding of the role of animals in Menorcan ritual practices during the second Iron Age; and (3) gaining an understanding of how communities managed their livestock resources and interacted with the landscape.

To this end, a multiproxy zooarcheological study of the faunal remains recovered from the *taula* enclosure at the Binissafullet site (Sant Lluís) has been conducted (Fig. 3). This is one of the few sites that has been excavated, and the faunal remains have already been analyzed by one of the authors of this research (Valenzuela, 2021a). The enclosure has a quadrangular plan with rounded corners, measuring 9 x 9.5 m (Gual, 1991; Gual and Plantalamor, 1997). During the archaeological excavations, three construction phases were identified: an initial structure made of vertical stones, subsequent alterations, and the final closure of the portal (Gual, 1991; Gual and Plantalamor, 1997). Numerous remains corresponding to the domestic triad, particularly young sheep and goats, were recorded (Gual and Plantalamor, 1997).

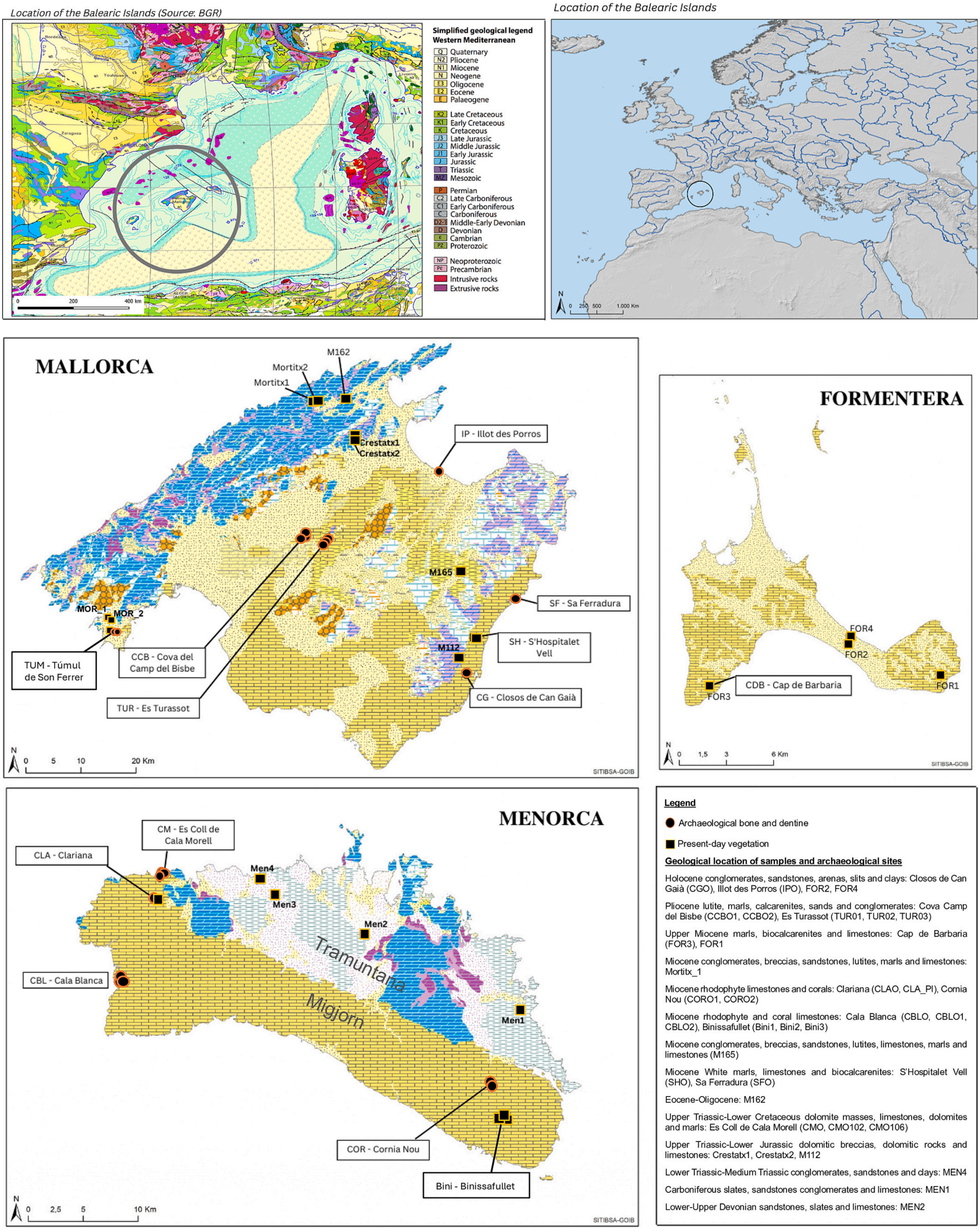

Fig. 1. (A) Geological map of the Western Mediterranean and location of the Balearic Islands. (B) Geological map of the Balearic Islands showing the location of main sites discussed in the text, .
adapted from a map created by A. Galmés (in Valenzuela-Suau et al. 2024)

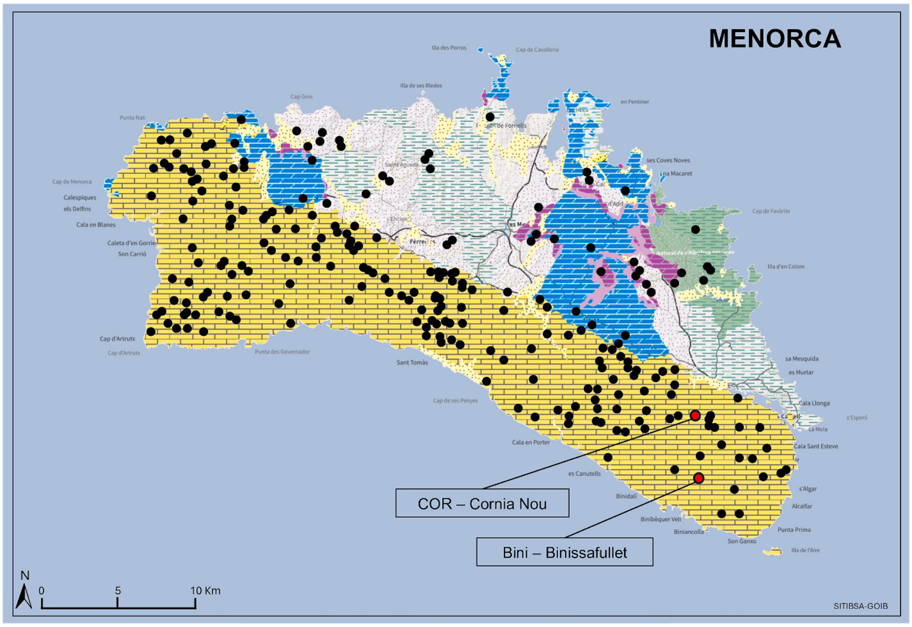

Fig. 2. Geological map of Menorca showing settlement locations during the Late Iron Age (based on Gornés et al. 2004).

Fig. 3. View of the *taula* enclosure of Binissafullet (L. Valenzuela-Suau).

These were found at various locations around the monolith, particularly in the corners formed by the pilasters and walls, and behind the *taula* (Gual and Plantalamor, 1997). The zooarchaeological assemblage was associated with layers of ash, Talayotic pottery, and Punic amphorae, indicating the existence of complex ritual practices (Gual and Plantalamor, 1997). Sling stones and other lithic elements with possible symbolic functionality were also recovered (Gual and Plantalamor, 1991; Gornés, 2008). The presence of imported pottery, such as Punic amphorae of the PE-14 and PE-16 types, enables to date the use of this ceremonial space to the Late Iron Age period, between the 4th and 3rd centuries BCE (Gual and Plantalamor, 1997). This chronology is consistent with that of other Menorcan sanctuaries, reinforcing the idea that these structures were places where local communities interacted with outsiders (Gual and Plantalamor, 1991; Gornés, 2008).

2. Materials and methods

2.1. Sample description

To achieve the objectives of this study, an isotopic analysis of 27 domestic caprines from the *taula* enclosure of Binissafullet site was carried out. Specifically, ten sheep (*Ovis aries*), nine goats (*Capra hircus*) and eight undifferentiated caprines were included to observe where there were any differences in herding practices between species (Table 1). As this is an exploratory study, only one sample per caprine was analyzed to maximize the number of individuals included. The isotopic analyses were based on a combination of strontium ($^{87}Sr/^{86}Sr$), oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) from each sample. To determine the local strontium reference for the Binissafullet site, three samples of current vegetation were analyzed (Table 2), and these results were combined with the rest of the published information on strontium isotopic ratios in the local geology.

The analysis focused on domestic caprines, which are the most common taxon in Balearic prehistory (Ramis, 2005; Ramis and Anglada, 2013; Valenzuela, 2017; Valenzuela-Suau, 2020) and are particularly abundant at the Binissafullet taula enclosure (Valenzuela, 2021a). The second and third lower molars of adult individuals (>12 months for second lower molars and from 18 to 24 months for third lower molars) were sampled from the buccal surface of the anterior lobe. This resulted in the analysis of 27 individuals (Table 1). All teeth were mechanically cleaned using a rotary bit attached to a hand drill to remove calculus and adhering sediment. The enamel sample for the isotopic analysis was collected by generating powder with the hand drill. Only one sample per individual was taken, as the objective of this study was to identify the livestock catchment areas of the *taula* enclosure and their dietary implications.

Table 1
Basic information of analyzed samples from Binissafullet site. (ERJ = enamel-root junction; *2 Tooth Wear Stages according to Grant 1982; *1 Age estimated according to Hambleton's comparison of Grant's and Halstead's methods (Hambleton, 1999).

Museum Sample ID	Sample ID	Species	Tooth	Tooth Wear Stage*1	Age*2	Laterality
496	Bi A1	*Ovis aries*	lower 3rd molar	P4(j), M1 (k), M2 (h), M3 (g)	6–8 years old	R
6098	Bi A2	*Ovis aries*	lower 3rd molar	P4(g), M1 (g), M2 (g), M3(f)	3–4 years old	L
1408	Bi A3	Caprine	lower 3rd molar	P4(g), M1 (g), M2 (h), M3 (g)	6–8 years old	L
497	Bi A4	*Ovis aries*	lower 3rd molar	P4(f), M1 (g), M2 (f), M3(c)	2–3 years old	L
1159	Bi A5	*Capra hircus*	lower 3rd molar	M2(g), M3 (e)	2–3 years old	R
888	Bi A6	*Capra hircus*	lower 2nd molar	M2 (e), M3(a)	1.5–2 years old	L
981	Bi A7	Caprine	lower 3rd molar	M3 (g)	6–8 years old	R
6424	Bi A8	*Capra hircus*	lower 3rd molar	P4(j), M1 (m), M2 (g), M3(f)	3–4 years old	R
149	Bi A9	*Ovis aries*	lower 3rd molar	P4(h), M1(j), M2(g), M3(f)	3–4 years old	L
1478	Bi A10	Caprine	lower 3rd molar	M1(n), M2(m), M3(j)	>8 years old	L
884	Bi A11	*Ovis aries*	lower 2nd molar	P4(j), M1 (j), M2(g)	>4 years old	R
6287	Bi A12	*Capra hircus*	lower 3rd molar	P4(g), M1 (g), M2€, M3(b)	2–3 years old	L
378	Bi A13	*Capra hircus*	lower 3rd molar	P4(h), M1(h), M2(g), M3(c)	2–3 years old	R
5022	Bi A14	*Ovis aries*	lower 3rd molar	M3(g)	>4 years old	L
4226	Bi A15	*Ovis aries*	lower 3rd molar	P4(k), M1 (k), M2 (h), M3(f)	3–4 years old	R
243	Bi A16	*Capra hircus*	lower 3rd molar	M1(m), M2(h), M3(g)	6–8 years old	L
5791	Bi A17	*Ovis aries*	lower 3rd molar	M3(c)	2–3 years old	L
5942	Bi A18	*Capra hircus*	lower 2nd molar	M2(d), M3(b)	2–3 years old	R
733	Bi A19	*Ovis aries*	lower 3rd molar	M3 (e)	3–4 years old	R
2	Bi A20	Caprine	lower 2nd molar	dP4 (h), M2 (e)	1–3 years old	R
247	Bi A21	Caprine	lower 2nd molar	M2 (e)	1–3 years old	E
6498	Bi A22	*Ovis aries*	lower 3rd molar	M3 (c)	2–3 years old	R
1237	Bi A23	*Capra hircus*	lower 2nd molar	P4(a), M1 (g), M2 (e)	1–3 years old	R
1380	Bi A24	Caprine	lower 2nd molar	M2 (g)	>3 years old	L
5718	Bi A25	Caprine	lower 2nd molar	M2 (d)	1–3 years old	L
3885	Bi A26	Caprine	lower 2nd molar	M2 (e)	2–4 years old	L
3927	Bi A27	*Capra hircus*	lower 3rd molar	M3 (f)	3–4 years old	R

Samples were generally taken approximately 2 mm above the enamel–root junction (ERJ), corresponding to the late stage of crown mineralization (Table 2 and Fig. 4). In some cases, samples were located slightly higher along the crown due to preservation or taphonomic constraints.For M3 teeth, this sampling position corresponds to a period when the animal was approximately 3–4 years old, whereas for M2 teeth it reflects an age of around 1.5–2 years (see e.g. Zedder, 2006; Tornero et al. 2016). It is therefore important to consider that the isotopic values obtained do not necessarily correspond to the age or location at death of the individual, but rather record the environmental conditions experienced during the final stages of enamel mineralization of each tooth.

Although the estimated age at sacrifice has been reported for each individual (Table 1), this age does not necessarily coincide with the timing represented by the enamel samples used for isotopic analysis. For example, based on tooth eruption and wear, individual Bi A1 was estimated to have been sacrificed at approximately 6–8 years of age; however, the enamel sample was taken at 2.42 mm above the ERJ, corresponding to an age of around 3–4 years. In contrast, individual Bi A20 was likely sacrificed between 1–3 years of age, and the enamel sample (taken at 2.71 mm above the ERJ) corresponds to approximately 1.5–2 years, meaning that in this case the isotopic signal is more closely related to the period immediately preceding sacrifice. Finally, leaves from modern vegetation collected at the Binissafullet site were used to constrain the expected ^{87}Sr/^{86}Sr range from the site (see Table 2).

2.2. Strontium analyses (^{87}Sr/^{86}Sr)

Strontium (^{87}Sr/^{86}Sr) analysis is used as a geographic tracer because ^{87}Sr is formed through the β-decay of rubidium isotope over time (Bentley, 2006). This causes the ^{87}Sr/^{86}Sr ratios to vary according to the lithological age of the bedrock (e.g. Bentley, 2006; Voerkelius et al. 2010), meaning older rocks typically exhibit higher values (Faure and Mensing, 2005). During the process of bone tissue formation, strontium (^{87}Sr/^{86}Sr) can replace calcium, enabling isotopes to be incorporated into body tissues via the food chain (Comar et al. 1957; Toots and Voorhies, 1965). Diagenetic processes can alter enamel after the tissues are buried. However, it has been shown that, as the enamel is less porous and more compact than other anatomical elements and has been shown to preserve the original isotope ratios (Budd et al. 2000; Evans et al. 2007; Lee-Thorp and Sponheimer, 2003; Madgwick et al. 2012; Nelson et al. 1986; Price et al. 2002). Consequently, the analysis of isotopes from dental enamel samples can be compared with the expected strontium for the region under study.

Strontium isotope analysis was conducted at the Laboratori d'Isòtops Radiogènics i Ambientals (LIRA) in the Dpt. de Dinàmica de la Terra i

Table 2
Baseline data from the Balearic Islands.

Era	Period	Epoch	Lithology	Island	Code	Species	GMS coordinates		87Sr/86Sr	Error (2σ)	Reference
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Mallorca	CGO	Sheep dentine	39°25′09′′N	3°14′40′′E	0.709179	0.000001	Valenzuela-Suau et al. 2021
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Mallorca	IPO	Sheep dentine	39°45′16′′N	3°11′17′′E	0.709193	0.000006	Valenzuela-Suau et al. 2021
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Formentera	FOR 2	*Pinus*	38°40′42.6″N	1°30′15.3″E	0.709159	0.000015	Valenzuela-Suau et al. 2024
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Formentera	FOR 4	*Pinus*	38°40′58.5″N	1°30′17.1″E	0.709131	0.000014	Valenzuela-Suau et al. 2024
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Mallorca	TUMO1	bos bone	39°29′35.6″N	2°29′56.4″E	0.70891	0.000016	Valenzuela-Suau et al. 2023
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Mallorca	TUMO2	s/g bone	39°29′35.6″N	2°29′56.4″E	0.70901	0.000016	Valenzuela-Suau et al. 2023
Cenozoic	Quaternary	Holocene	conglomerates, sandstones, arenas, silts and clays	Mallorca	TUM_1	*Pistacia lentiscus*	39°29′35.7″N	2°29′39.9″E	0.709138	0.000018	Valenzuela-Suau et al. 2023
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	CCBO	Sheep bone	39° 38′ 57.76′′N	2°54′21.27′′E	0.708963	0.000009	Valenzuela-Suau et al. 2021
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	CCBO1	s/g bone	39°38′57.9″N	2°54′20.9″E	0.709066	0.000013	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	CCBO2	Sheep bone	39°38′57.9″N	2°54′20.9″E	0.709069	0.000013	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	TURO1	Sheep bone	39°38′26.4″N	2°57′02.1″E	0.709205	0.000013	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	TURO2	s/g bone	39°38′26.4″N	2°57′02.1″E	0.709204	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Pliocene	lutites, marls, calcarenites, sands and conglomerates	Mallorca	TURO3	Cattle bone	39°38′26.4″N	2°57′02.1″E	0.709042	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Upper Miocene	marls, biocalcarenites and limestones	Formentera	FOR 1	*Pinus*	38°39′43.7″N	1°34′16.7″E	0.709066	0.000014	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Upper Miocene	marls, biocalcarenites and limestones	Formentera	FOR_3	*Pinus*	38°65′98.97″N	1°23′46.3″E	0.709205	0.000015	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	conglomerates, breccias, sandstones, lutites, limestones, marls and limestones	Mallorca	Mortitx 1	*Quercus Ilex*	39°52′12.1″N	2°55′31.4″E	0.708705	0.000015	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	conglomerates, breccias, sandstones, lutites, limestones, marls and limestones	Mallorca	M165	*Pinus*	39°35′19.97″N	3°13′53″E	0.709096	0.000009	Valenzuela-Suau et al. 2021
Cenozoic	Neogene	Miocene	rhodophyte limestones and corals	Menorca	CLAO	s/g bone	40°02′17″N	3°52′29″E	0.709328	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte limestones and corals	Menorca	CLA_PI	*Pinus*	40°03′82′′N	3°87′48′′E	0.709344	0.000019	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte limestones and corals	Menorca	CORO 1	s/g bone	39°52′52.9″N	4°14′00.7″E	0.710170	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte limestones and corals	Menorca	CORO 2	s/g bone	39°52′52.9″N	4°14′00.7″E	0.709895	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	CBLO	Sheep bone	39°58′04′′N	3°50′10′′E	0.709194	0.000004	Valenzuela-Suau et al. 2021
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	CBLO1	Sheep bone	39°58′04′′N	3°50′10′′E	0.709182	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	CBLO2	Sheep bone	39°58′04′′N	3°50′10′′E	0.709180	0.000022	Valenzuela-Suau et al. 2024
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	**Bini 1**	*Olea europaea*	39°50′45.0″N	4°14′07.1″E	**0.709308**	0.000019	This paper
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	**Bini 2**	*Olea europaea*	39°50′45.7″N	4°14′08.1″E	**0.709658**	0.000019	This paper

(*continued on next page*)

Table 2 (*continued*)

Era	Period	Epoch	Lithology	Island	Code	Species	GMS coordinates		87Sr/86Sr	Error (2σ)	Reference
Cenozoic	Neogene	Miocene	rhodophyte and coral limestones	Menorca	**Bini 3**	*Olea europaea*	39°50′45.7″N	4°14′08.1″E	**0.709365**	0.000019	This paper
Cenozoic	Neogene	Miocene	white marls, limestones and biocalcarenites	Mallorca	SHO	*Olea europaea*	39°28′56.3″N	3°15′42.1″E	0.709091	0.000005	Valenzuela-Suau et al. 2021
Cenozoic	Neogene	Miocene	white marls, limestones and biocalcarenites	Mallorca	SFO	Sheep dentine	39°32′41″N	3°21′01″E	0.709287	0.000006	Valenzuela-Suau et al. 2021
Cenozoic	Paleogene	Eocene-Oligocene	conglomerates, breccias, sandstones, lutites and limestones	Mallorca	Mortitx 2	*Quercus Ilex*	39°52′11.2″N	2°55′25.1″E	0.708961	0.000015	Valenzuela-Suau et al. 2024
Cenozoic	Paleogene	Eocene-Oligocene	conglomerates, breccias, sandstones, lutites and limestones	Mallorca	M162	*Quercus ilex*	39°52′25.5″N	2°59′0.53″E	0.708327	0.000007	Valenzuela-Suau et al. 2021
Cenozoic	Paleogene	Eocene-Oligocene	conglomerates, breccias, sandstones, lutites and limestones	Mallorca	MOR_1	*Olea europaea*	39°30′29.3″N	2°28′58.3″E	0.708552	0.000018	Valenzuela-Suau et al. 2023
Cenozoic	Paleogene	Eocene-Oligocene	conglomerates, breccias, sandstones, lutites and limestones	Mallorca	MOR_2	*Olea europaea*	39°30′19.5″N	2°29′09.7″E	0.708713	0.000018	Valenzuela-Suau et al. 2023
Mesozoic	Triassic-Jurassic-Cretaceous	Upper Triassic-Lower Cretaceous	dolomite masses, limestones, dolomites and marls	Menorca	CMO	Sheep bone	40°03′27″N	3°52′58″E	0.709236	0.000003	Valenzuela-Suau et al. 2021
Mesozoic	Triassic-Jurassic-Cretaceous	Upper Triassic-Lower Cretaceous	dolomite masses, limestones, dolomites and marls	Menorca	CMO 102	Sheep bone	40°03′27.6″N	3°52′56.9″E	0.709188	0.000022	Valenzuela-Suau et al. 2024
Mesozoic	Triassic-Jurassic-Cretaceous	Upper Triassic-Lower Cretaceous	dolomite masses, limestones, dolomites and marls	Menorca	CMO 106	Sheep bone	40°03′27.6″N	3°52′56.9″E	0.709182	0.000022	Valenzuela-Suau et al. 2024
Mesozoic	Triassic-Jurassic	Upper Triassic-Lower Jurassic	dolomitic breccias, dolomitic rocks and limestones	Mallorca	Crestatx 2	*Quercus Ilex*	39°48′34.9″N	3°00′37.2″E	0.710152	0.000019	Valenzuela-Suau et al. 2024
Mesozoic	Triassic-Jurassic	Upper Triassic-Lower Jurassic	dolomitic breccias, dolomitic rocks and limestones	Mallorca	Crestatx 1	*Quercus Ilex*	39°48′27.4″N	3°00′54.1″E	0.709149	0.000019	Valenzuela-Suau et al. 2024
Mesozoic	Triassic-Jurassic	Upper Triassic-Lower Jurassic	dolomitic breccias, dolomitic rocks and limestones	Mallorca	M112	*Pinus*	39°26′59.0″N	3°13′50.1″E	0.709451	0.000012	Valenzuela-Suau et al. 2021
Mesozoic	Triassic	Lower Triassic-Medium Triassic	Conglomerates, sandstones and red clays	Menorca	MEN_4	*Pinus*	40°03′01.8″N	3°59′19.7″E	0.709226	0.000010	Valenzuela-Suau et al. 2024
Paleozoic	Carboniferous	Carboniferous	sandstones, shales, conglomerates, vulcanites and limestones	Menorca	MEN_3	*Quercus ilex*	40°02′13.9″N	4°00′19.4″E	0.709231	0.000010	Valenzuela-Suau et al. 2024
Paleozoic	Devonian-Carboniferous	Carboniferous	slates, sandstones, conglomerates and limestones	Menorca	MEN_1	*Quercus ilex*	39°56′25.4″N	4°15′53.6″E	0.709855	0.000010	Valenzuela-Suau et al. 2024
Paleozoic	Devonian-Carboniferous	Lower-Upper Devonian	sandstones, slates and limestones	Menorca	MEN_2	*Pinus*	40°00′17.3″N	4°05′56.8″E	0.710469	0.000010	Valenzuela-Suau et al. 2024

Fig. 4. Lower third molar from the taula enclosure (Bi A14), showing the sampled area.

l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona (Spain). Strontium was purified using standard chromatographic procedures with Triskem® Sr-Spec resin, which allows efficient separation of Sr^{2+} from interfering elements such as Rb. Isotope ratios were measured by multicollector inductively coupled plasma mass spectrometry (MC-ICPMS) using a Nu Plasma 3 instrument at the Centres Científics i Tecnològics (CCiT-UB).

Isobaric interferences of ^{87}Rb on ^{87}Sr were corrected using the measured ^{85}Rb signal and an assumed $^{87}Rb/^{85}Rb$ ratio of 0.3857 (de Laeter et al. 2003, and ^{86}Kr interference on ^{86}Sr was corrected using the measured ^{83}Kr signal (Weber et al. 2020). Instrumental mass bias was corrected by internal normalization to $^{86}Sr/^{88}Sr = 0.1194$ using the exponential law (Wombacher and Rehkämper, 2003). Instrumental drift was monitored by sample–standard bracketing with the NIST SRM 987 reference material ($^{87}Sr/^{86}Sr = 0.710249$) (Azmy et al. 1999; Ando et al. 2011; Cramer et al. 2011). Analytical reproducibility during the session was ±0.000018 (2σ). A detailed description of the analytical protocol routinely applied at LIRA is provided in Filioglou et al. (2024).

2.3. Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) analyses

The analysis of oxygen isotopes ($\delta^{18}O$) present in dental bioapatite provides information about the isotopic composition of body water. These values derived from multiples inputs, including drinking water, oxygen incorporated through respiration, and the water and organic of consumed food (Bryant and Froelich, 1995; Longinelli, 1984; Luz et al. 1984). As a result, enamel $\delta^{18}O$ values mainly reflect the isotopic composition of ingested water, which is shaped by local environmental conditions such as hydrology, evaporation, altitude, rainfall amount, and seasonal variability, together with physiological factors (Gat, 1996; Kohn and Welker, 2005; Rozanski et al., 1993).

While large-scale climatic patterns—such as those described by Dansgaard (1964)—clearly document systematic variations in $\delta^{18}O$ values of precipitation across temperature and latitudinal gradients, these relationships cannot be directly translated to $\delta^{18}O$ values recorded in bioapatite. In temperate regions like Menorca, enamel $\delta^{18}O$ values are better understood in terms of seasonal changes in temperature, evaporation, and water availability, rather than latitude alone. Therefore, high values are expected during the warm season and lower values during the cold season.

Carbon isotope analysis ($\delta^{13}C$) based on dental enamel provide information about the diet and ecology of animals (see e.g. Sullivan and Krueger, 1981; Lee-Thorp et al. 1989; Koch, 1998; Makarewicz and Pederzani, 2017; Wang and Badgley, 2022; Valenzuela-Lamas et al. 2023). During photosynthesis, plants adapt to their environment by using different carbon fixation pathways (Farquhar et al. 1989; Smith and Epstein 1971). Consequently, C_3 plants (which are typical of temperate zones and are the most widespread in the Mediterranean) provide lower $\delta^{13}C$ values than C_4 plants, with an average $\delta^{13}C$ of −26‰ VPDB. By contrast, C_4 plants, which are more prevalent in tropical and arid environments, exhibit more enriched δ13C values, averaging −12‰ VPDB (Smith and Epstein, 1971; Monson et al. 1984; O'Leary, 1988; Cerling et al. 1997; Koch, 1998).

In herbivore tooth enamel, these dietary differences are reflected after accounting for diet-enamel enrichment. Diets dominated by C_3 vegetation tend to produce enamel $\delta^{13}C$ values of approximately −14‰ to −9‰, while more enriched values are generally associated with a greater contribution of C_4 plants (Lee-Thorp et al. 1989; Cerling and Harris, 1999; Koch, 1998). The isotopic composition of plants is also influenced by other factors, such as rainfall, light exposure, humidity conditions, soil salinity, and seasonal changes (Farquhar et al. 1982; Farquhar and Von Caemmerer, 1982; Farquhar, 1991; Smedley et al. 1991; Tieszen, 1991; Heaton, 1999; Murphy and Bowman, 2009; Hartman and Danin, 2010). Thus, water stress also affects ^{13}C isotopic values, which are more positive in comparison with well-irrigated plants (Ferrio et al. 2005).

Oxygen and carbon isotope analyses were performed at the *Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR)*, University of Granada. Carbon dioxide was released by reacting the enamel carbonate with 100% phosphoric acid for 12 h at 50 °C in a thermostatic bath, following the method of McCrea (1950). Isotopic ratios were measured using a Delta XP isotope ratio mass spectrometer (IRMS). Analytical precision for $\delta^{18}O$ in carbonates was ±0.05‰, using Carrara and EEZ-1 as internal standards previously calibrated against the international reference materials NBS-18 and NBS-19.

2.4. Definition of mobility scales

For the interpretation of strontium isotope data, this study adopts a multi-scalar approach to mobility. Following previous methodological discussions on mobility scales (e.g. Cavazzuti et al. 2019), and adapting them to the specific geographical and geological constraints of Menorca, four operational mobility scales are defined as follows:

a) A **local scale** is defined as the immediate catchment area of the site, corresponding approximately to 3–4 Km. This scale is based on theoretical models of settlement exploitation for Menorca during the Second Iron Age (see Riudavets and Ferrer, 2022) and reflects daily herding movements.
b) An **intra-island** mobility scale (from c. 8 Km to the whole island of Menorca). This scale is defined based on two main principles. First, 8 Km represents the minimum distance between the site of Binissafullet and the northern part of the island (Tramuntana region), which is characterized by older geological formations that would theoretically be expected to yield more radiogenic strontium values. Second,

this scale is considered to encompass the island as a whole, as the southern area where the site is located (Migjorn) is isotopically indistinguishable from the site itself, and the different geological units within the northern part of the island cannot be robustly discriminated from one another at present. Mobility is therefore interpreted as an island-wide scale.

c) An **inter-island** mobility scale is defined at the level of the Balearic archipelago, referring to mobility between islands.
d) An **overseas** mobility scale is used to geographic areas outside the Balearic archipelago. This scale is defined through strontium isotopic values consistent with geological formations not present in the Balearic Islands, such as those documented for Sardinia or Corsica.

3. Results

The local strontium signal at the Binissafullet site, as determined from modern vegetation samples, ranges from 0.709308 to 0.709658 ^{87}Sr/^{86}Sr (Table 2 and 3). The strontium isotope ratios of dental enamel samples of domestic caprines at the Binissafullet site range from 0.709234 and 0.709978 ^{87}Sr/^{86}Sr (mean 0.7094471 ± 0.0001) (Table 3). Within this overall range, the values for *Ovis aries* fall between 0.709234 and 0.709968 ^{87}Sr/^{86}Sr, while the values for *Capra hircus* range between 0.709235 and 0.709627 ^{87}Sr/^{86}Sr (Table 3). Normality was assessed using the Shapiro-Wilk test and was rejected for both species. Therefore, a non-parametric Mann-Whitney *U* test was used to compare ^{87}Sr/^{86}Sr values between *Ovis aries* and *Capra hircus,* and no significant differences were observed (U = 38; *p* = 0.5956).

Oxygen isotope values from dental enamel samples of domestic caprines range from −6.15‰ to −2.32‰ δ^{18}O (mean −4.47 ± 0.85‰) (Table 3). Within this interval, values for *Ovis aries* range from −6.09‰ to −3.39‰, while the values for *Capra hircus* range from −5.02‰ to −3.27‰ (Table 3). Normality was assessed using Shapiro-Wilk test. However, given the small sample size, a non-parametric Mann-Whitney *U* test was used to compare δ^{18}O results between species and no significant differences were detected (U = 36; *p* = 0.4871).

Table 3
Isotopic ratios of strontium (^{87}Sr/^{86}Sr), oxygen (δ^{18}O) and carbon (δ^{13}C) for each analyzed sample.

Sample ID	^{87}Sr/^{86}Sr	Uncertainty (2 s)	δ^{13}C ‰ (PDB)	δ^{18}O ‰ (PDB)	ERJ
Bi A1	0.709409	0.000017	−10.38	−3.96	2.42
Bi A2	0.709374	0.000017	−8.80	−3.39	2.40
Bi A3	0.709262	0.000016	−9.47	−6.15	3.45
Bi A4	0.709281	0.000017	−8.34	−6.09	5.90
Bi A5	0.709252	0.000017	−9.96	−4.74	2.90
Bi A6	0.709235	0.000016	−9.76	−4.74	4.80
Bi A7	0.709486	0.000021	−11.66	−5.84	3.81
Bi A8	0.709627	0.000021	−10.44	−5.02	4.48
Bi A9	0.709505	0.000018	−10.67	−5.15	4.49
Bi A10	0.709978	0.000021	−10.96	−4.49	2.52
Bi A11	0.709301	0.000018	−9.35	−4.17	3
Bi A12	0.709328	0.000017	−10.67	−4.18	5.13
Bi A13	0.709303	0.000018	−11.18	−4.91	5
Bi A14	0.709968	0.000017	−10.90	−4.17	3.12
Bi A15	0.709594	0.000021	−10.73	−5.15	3.46
Bi A16	0.709624	0.000021	−10.47	−3.68	3.55
Bi A17	0.709462	0.000019	−11.47	−4.58	3.34
Bi A18	0.709312	0.000018	−10.76	−3.40	4.65
Bi A19	0.709234	0.000018	−10.41	−4.69	5.24
Bi A20	0.709690	0.000018	−9.92	−4.28	2.71
Bi A21	0.709509	0.000019	−9.72	−2.32	3.90
Bi A22	0.709353	0.000018	−11.00	−4.68	4.71
Bi A23	0.709369	0.000019	−9.95	−3.27	3.54
Bi A24	0.709484	0.000018	−9.10	−4.61	5.08
Bi A25	0.709452	0.000018	−10.33	−4.72	4.05
Bi A26	0.709297	0.000016	−10.45	−4.30	4.59
Bi A27	0.709382	0.000019	−9.02	−4.10	3.79
Bini 1	0.709308	0.000019	–	–	–
Bini 2	0.709658	0.000019	–	–	–
Bini 3	0.709365	0.000019	–	–	–

Most individuals from both species cluster between −5‰ and −4‰ δ^{18}O. Because second (M2) and third (M3) lower molars samples mineralize at different stages of life, and sampling height relative to enamel-root junction (ERJ) may introduce temporal bias, δ^{18}O values were plotted against sampling height (mm), distinguishing between M2 and M3 (Figure x). No clear relationship is observed, and δ^{18}O values display substantial overlap across sampling heights.

Carbon isotope values of the dental enamel samples of the domestic caprine range from −11.66‰ to −8.34‰ δ^{13}C (mean −10.22 ± 0.82‰) (Table 3). The low standard deviation indicates relatively homogeneous δ^{13}C values. Values for *Ovis aries* vary from −10.38‰ to −9.35‰ δ^{13}C, and values for *Capra hircus* from −10.44‰ to −9.96‰ δ^{13}C. Normality was assessed using Shapiro-Wilk test. However, given the small sample size, a non-parametric Mann-Whitney *U* test was used to compare δ^{13}C between species and no significant differences were detected (Mann-Whitney *U* test = 42; *p* = 0.8792). In addition, no significant correlation was observed between δ^{13}C and δ^{18}O values (Spearman's ρ = 0,164, p = 0,413; n = 27).

4. Discussion

The Binissafullet faunal assemblage is dominated almost entirely by domestic species, with 99.8% of the identified remains corresponding to livestock (Valenzuela 2021a). Caprines account for the majority (56.3%), followed by pigs (26.7%) and cattle (16.9%), while wild taxa are virtually absent. The density of remains is high (25.7 MNE/m^2), which is consistent with the intense depositional dynamics observed in other Talayotic sanctuaries (Valenzuela, 2021b).

Ageing data indicate a clear selection of juveniles and prime-age adults: most caprines were slaughtered between 6 and 24 months of age, particularly in the 6–12 months range (48.7%), while a second peak corresponds to adults between 2 and 4 years of age (42.1%), coinciding with their optimal meat yield. Pigs and cattle exhibit a comparable pattern, with a preponderance of young individuals but also some subadults. This demographic profile reflects the deliberate ritual consumption choices represented in the sanctuary deposits.

Age-at-death estimates were obtained through the analysis of dental eruption and wear stages, following methodological criteria previously applied in archaeozoological studies of Balearic assemblages (Valenzuela, 2015). The use of standardized ageing protocols ensures direct comparability with other Talayotic and Post-Talayotic contexts. The resulting mortality profile points to a deliberate targeting of juveniles and prime-age adults rather than opportunistic consumption. Such a pattern reflects structured choices linked to ritual practices, with a preferential focus on individuals slaughtered at optimal meat-yield ages, consistent with patterns observed in other Talayotic taula sanctuary assemblages (Valenzuela, 2021b).

Taking together, these zooarchaeological patterns provide the necessary contextual framework to interpret the isotopic data, particularly in relation to herd management strategies and the spatial scale of animal provisioning.

4.1. Catchment areas

Strontium isotope results suggest that most animals buried within the *taula* enclosure display ^{87}Sr/^{86}Sr values consistent with grazing in the vicinity of the site (0.7093–0.7096 ^{87}Sr/^{86}Sr, Table 3 and Fig. 5), corresponding to the local scale designed in this study. No statistically significant differences were detected between species. However, a small number of individuals exhibit values outside the local range, indicating grazing beyond the immediate vicinity during tooth mineralization, which may be compatible with the intra-island scale defined in this work. However, it should be noted that the site is located on a widespread geological formation covering ~ two-thirds of Menorca (Bourrouilh, 1968) (see Figs. 2 and 6). This formation also hosts the

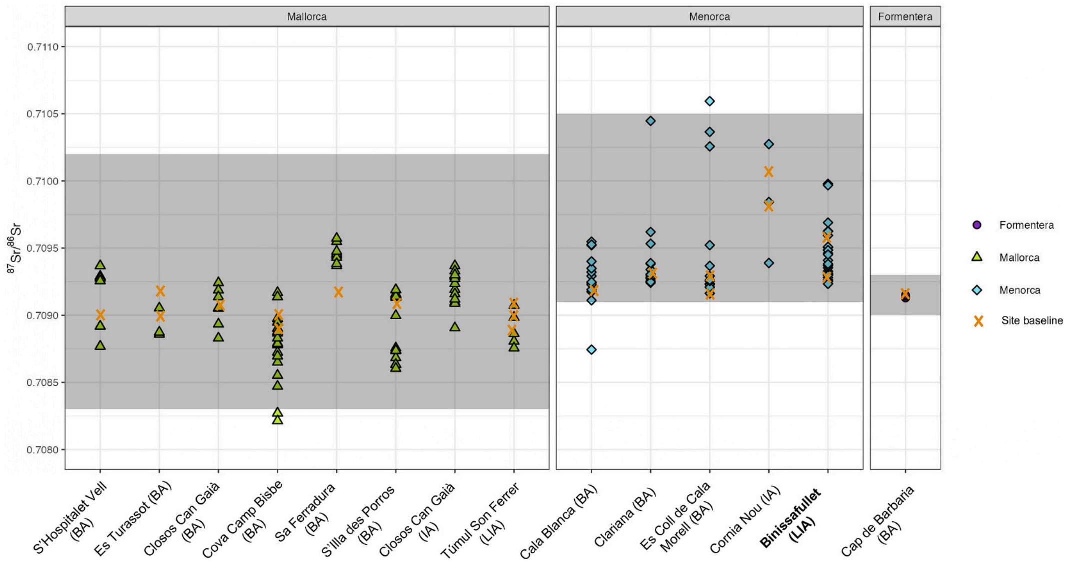

Fig. 5. $^{87}Sr/^{86}Sr$ results from Binissafullet site (Bini) and other sites published in previous studies (Valenzuela-Suau et al. 2021, 2023 and 2024). The grey band represents the estimated baseline for each island based on the available simples (Table 2). Orange crosses indicate the reference values corresponding to each site.

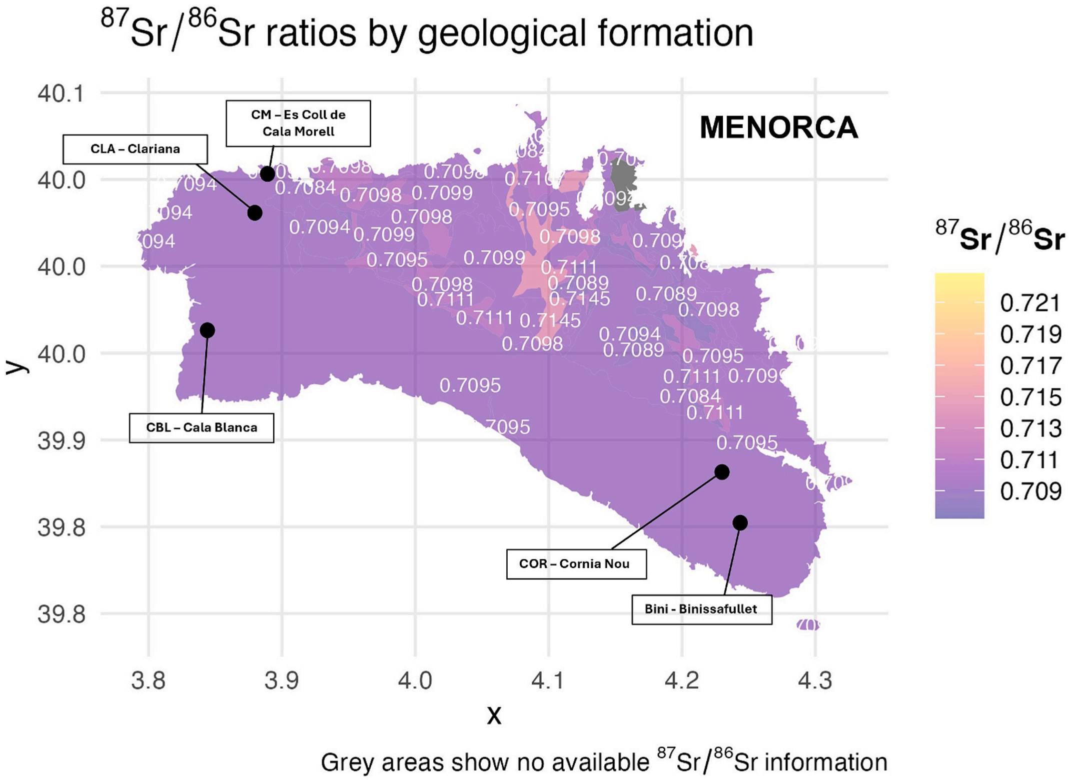

Fig. 6. Average $^{87}Sr/^{86}Sr$ values per geological formation following R script published in Valenzuela-Lamas et al. (2026). Information from baseline of the Balearic islands (Table 2) and same geological units of the Iberian Peninsula. Geological data .
source: IGME. Strontium isotopic ratios from the present study and the SrIsoMed database (Nikita et al 2022)

majority of contemporaneous settlements (Gornés et al., 2004) (Fig. 2). Therefore, the strontium data cannot rule out the possibility that some individuals originated from other settlements on the same geological layer (Fig. 6).

Nevertheless, a few animals, show values outside the estimated local range for Binissafullet. These values also exceed those reported for other sites within the same geological formation (0.7090–0.7093 $^{87}Sr/^{86}Sr$) (see Valenzuela-Suau et al., 2021; 2024; Fig. 6). This pattern suggests that some individuals may have grazed in areas that are geologically different to those around the Binissafullet settlement (Taula 2, Fig. 6). Overall, however, strontium values are relatively homogeneous, thus reflecting the limited variability of Menorca's geology (Figs. 1, 2 and 6). It should also be considered that sites located close to the coast, particularly on small islands, may be influenced by marine aerosols (sea spray), which can lead to a mixing of terrestrial and marine strontium signatures. Individuals grazing in coastal areas (e.g. within a few hundred meters of the shoreline) may therefore exhibit values approaching that of seawater (~0.7092 $^{87}Sr/^{86}Sr$) (e.g. Alonzi et al. 2020). Consequently, values close to this ratio cannot be unequivocally attributed to movement across geological zones and may partly reflect marine aerosol input. While most individuals fall within the estimated local range of the site –or may be influenced by coastal effects- a small number of outliers remain consistent with grazing in geologically distinct areas.

Overall, the available dataset captures the range of strontium values currently documented for Menorca, allowing the assemblage to be interpreted as predominantly local at island scale, despite minor deviations. While some animals may have come from areas of the island with more radiogenic signatures, such as the Tramuntana region in the northern part of Menorca (Valenzuela-Suau et al. 2024), all ratios are consistent with a Menorcan origin for sheep and goats (Fig. 6). This suggests that, regardless of the presence of non-local materials such as imported wine of ceramics, the isotopic signatures of the animal remains consumed within the Binissafullet taula enclosure are compatible with a local, Menorcan origin (intra-island scale).

In both Late Iron Age assemblages analyzed to date, the strontium data are consistent with a local, island-wide origin of the livestock. At Binissafullet, where only one sample per individual was analyzed, most caprines fall within the estimated local range (both site vegetation samples and other published samples, Table 2). However, some display higher $^{87}Sr/^{86}Sr$ values approaching 0.7100, which is consistent with grazing in the Tramuntana region of Menorca, located approximately 8 km away (Valenzuela-Suau et al. 2024) (Fig. 6). In the case of the Mallorca tumulus, all strontium results, when considering a single sample per individual, fall within the local range, thus suggesting a local herding in all cases (Fig. 5). Conversely, sequential analyses revealed that some individuals grazed beyond the estimated local site range, with the oxygen results being compatible with seasonal movements in some cases (Valenzuela-Suau et al. 2024).

In the case of Menorca, it has been hypothesized that the exploitation areas of each settlement during the Late Iron Age period could have had a radius of around 3.4 km (Riudavets and Ferrer, 2022). These values are just a theoretical proposal intended to illustrate the level of human pressure over the land that existed in Menorca during the Late Iron Age (Riudavets and Ferrer, 2022), and they contribute to the ongoing discussion (see Fig. 2). Within this theoretical framework, the relatively higher strontium values observed –mainly associated with the northern part of the island (Tramuntana region)- are compatible with the possibility that some animals grazed in this area. As illustrated in Fig. 6, this would imply potential grazing distances of up to ~8 km or more within the island. However, the absence of sequential enamel analyses and a fully developed bioavailable strontium isoscape, this scenario cannot be independently confirmed and should therefore be regarded as provisional.

4.2. *Caprines diet*

For the oxygen isotope results ($\delta^{18}O$) interpretation, it is important to note that the analyzed species, *Ovis aries* and *Capra hircus*, are considered non-obligated drinkers. As a result, their enamel $\delta^{18}O$ values reflect a combination of oxygen derived from the plants, the water and the metabolic process (Levin et al. 2006). Finally, as with strontium and carbon isotopes, each measurement represents a single sample per individual, preventing the detection of intra-tooth variation.

During prehistoric times, Menorca is thought to have a climate broadly comparable to the present, characterized by warm, dry summers and cool, wet winters (Mariscal, 1996; Tarroso et al. 2016; Frigola et al. 2007; Servera-Vives and Riera, 2024). Comparative oxygen isotope data from enamel in other Mediterranean contexts –such as Late Iron Age Mallorca (Valenzuela-Suau et al. 2023), human remains from *Eivissa* (Dury et al., 2019), from Catalonia (Navarrete et al. 2019, Valenzuela Lamas et al. 2023, Messana et al. 2023), and Copper Age Sardinia (Lai et al. 2024)- show broadly similar $\delta^{18}O$ ranges to those obtained in this study, despite differences in species and chronology.

At Binissafullet site, values range from −6.15‰ to −2.32‰ (total amplitude 3.83‰) (Table 3, Figs. 7 and 8). Given that only one sampling point per tooth was analyzed, and considering the potential variability related to sampling height relative to enamel-root junction and the use of both second and third molars, this spread that can reasonably be explained by seasonal variability, differences in plant water sources, or short-range environmental heterogeneity with grazing areas, rather than by large-scale mobility or major dietary changes (Fig. 8).

Carbon isotope values ($\delta^{13}C$) from Binissafullet range between −11.6‰ and −8.3‰, with a mean value of −10.22‰ (Table 3, Fig. 7). No significant differences were observed between the *Ovis aries* and *Capra hircus*, indicating broadly similar dietary patterns and,

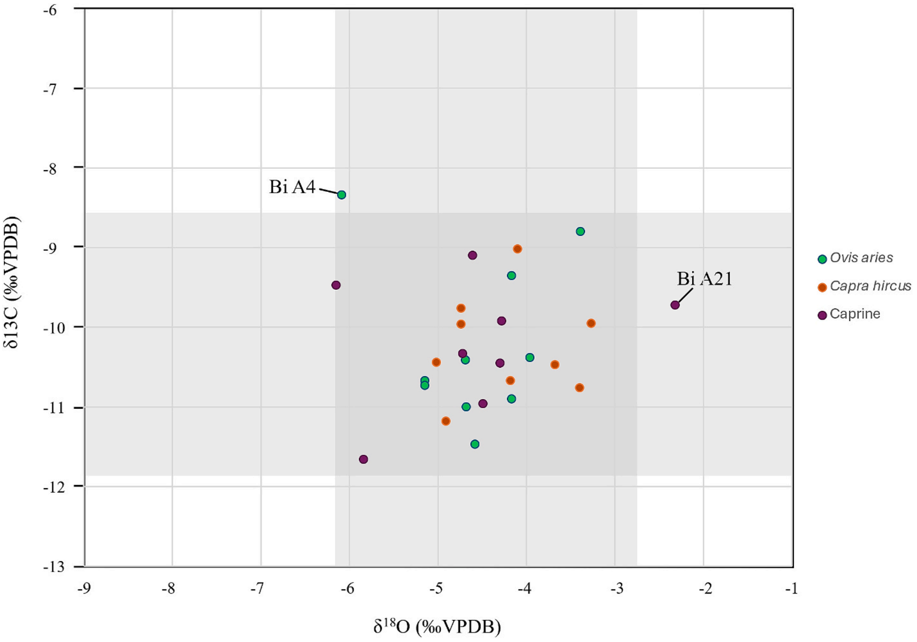

Fig. 7. $\delta^{18}O$ and $\delta^{13}C$ results from the Binissafullet site. The grey shape represents the 95% concentration interval, with highlithed and labelled outliers.

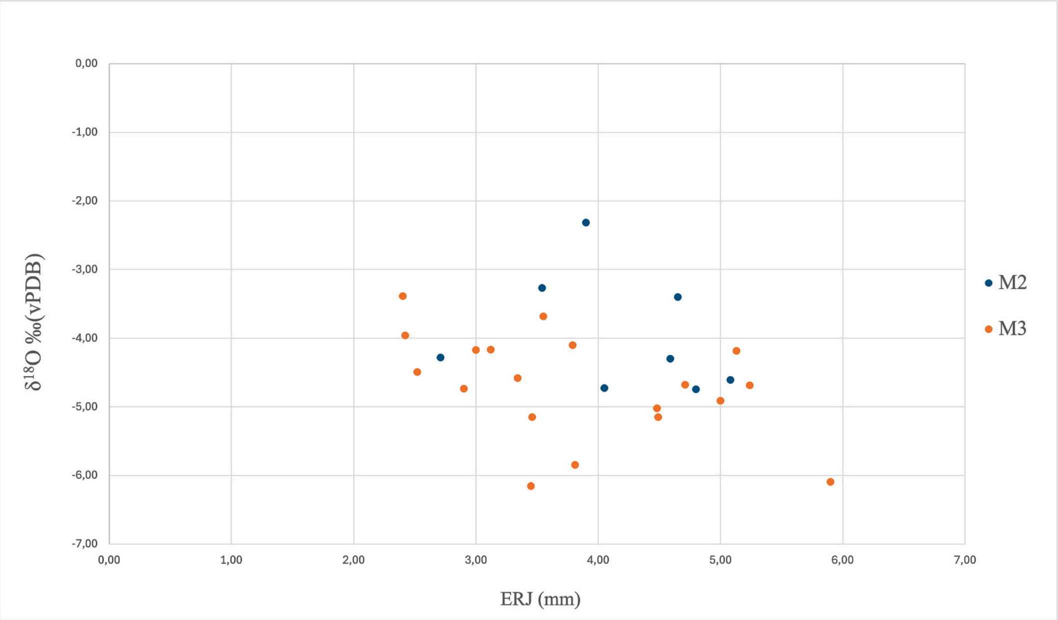

Fig. 8. Oxygen isotope dispersion differenciated by lower second molars (M2) and lower third molars (M3), plotted against distance from the enamel-root junction (ERJ).

consequently, the two species are discussed together. Overall, the $\delta^{13}C$ values are consistent with a diet predominanty based on C_3 vegetation, in the line with expectations for Mediterranean environments.

This interpretation is supported by previously published isotopic studies on animal bone collagen from Menorca, which likewise indicate a reliance on C_3 plant resources (Strydonck et al., 2005; Sotriadou et al. 2023). Such results are also compatible with the reconstructed vegetation and landscape of Menorca during the Talayotic period (c. 850–123 BCE), characterized by the presence of olive (*Olea europaea*), holm oak (*Quercus ilex*), wild olive (*Olea europaea sylvestris*), Aleppo pine *(Pinus halepensis*), mastic (*Pistacia lentiscus*) and rockrose (*Cistus sp*.), heather (*Erica sp*.), cereals such as barley (*Hordeum vulgare*) and wheat (*Triticum sp*.) (e.g. Picornell-Gelabert, 2012; Burjachs et al. 2016; Revelles and Burjachs, 2015; Portillo et al., 2014; Pérez-Jordà et al., 2018; Picornell-Gelabert and Servera-Vives, 2017; Servera-Vives and Currás, 2016; 2017; Valenzuela-Suau et al. 2018; Servera-Vives and Riera, 2024).

Nevertheless, the presence of some relatively enriched $\delta^{13}C$ values within the C_3 range obtained in this study requires further discussion, as C_3 diets in enamel produces approximately a range from −14‰ to −9‰ (Lee-Thorp et al. 1989; Cerling and Harris, 1999; Koch, 1998), whereas more enriched $\delta\ ^{13}C$ values are generally associated with C_4 diets.

Firstly, there is no evidence of the consumption of C_4 plants, such as millet, which would be expected to produce more enriched $\delta^{13}C$ values than those recorded here (Lee-Thorp et al. 1989; Cerling and Harris, 1999; Koch, 1998). In Mediterranean contexts, diets including a significant C_4 contribution are typically associated with enamel $\delta\ ^{13}C$ values around above −9‰ (Cerling and Harris, 1999; Tieszen and Boutton, 1989). Unlike in Ibiza, where the common millet has been documented from the 7th-6th centuries BCE onwards (Sureda et al. 2017), its introduction in Menorca during the Late Iron Age remains undocumented (Pérez-Jordà et al. 2018). Therefore, a C_4 diet is unlikely to explain the relatively enriched values observed at Binissafullet (up to −8‰) (Table 3, Fig. 7).

Given the insular setting of Menorca and the proximity of the site to the coast (< 3 km), the consumption of seaweed represents a plausible hypothesis as documented in other island contexts such as Orkney (United Kingdom). However, isotopic studies on caprines with significant seaweed intake show markedly more enriched enamel $\delta^{13}C$ values (approximately −4.9‰ to −0.4‰), which are substantially different than those recorded in this study (Balasse et al. 2019). Therefore, the $\delta^{13}C$ values obtained from Binissafullet data are not compatible with marine or coastal resources to caprine diets. Instead, they are in line with paleobotanical evidence that points to a limited use of coastal and marine resources and the absence of C_4 plants during the Late Iron Age in Menorca (Strydonck, 2005; Picornell-Gelabert, 2012; Ramis, 2017; Valenzuela-Suau et al., 2022; Sotiriadou et al., 2023).

Various environmental factors that can influence the carbon isotope ratio ($\delta^{13}C$) of C_3 plants. Under drought conditions, for example, plants tend to close their stomata, leading to reduce CO_2 uptake and a slight enrichment in $\delta^{13}C$ values (Farquar et al. 1989). This mechanism is consistent with existing paleoenvironmental evidence indicating a Mediterranean climate, characterized by dry conditions and a deforested, anthropized landscape (Mariscal, 1996; Picornell-Gelabert, 2012; Portillo et al., 2014; Anglada et al., 2013; Picornell-Gelabert and Servera-Vives, 2017; Picornell-Gelabert and Carrión, 2017; Pérez et al., 2017; Servera-Vives and Currás-Domínguez, 2016; 2017; Servera-Vives and Riera, 2024; Valenzuela-Suau et al. 2022b).

However, only one enamel sample per individual was analyzed, which limits the assessment of potential seasonal variation. During summer, such environmental conditions would also be expected to produce more enriched $\delta^{13}C$ values in C_3 plants, together with higher $\delta^{18}O$ values (Smedley et al. 1991). In the Binissafullet dataset, no clear correlation is observed between $\delta^{13}C$ and $\delta^{18}O$ values (Fig. 7). Individuals showing relatively enriched $\delta^{13}C$ values (−8.3‰ to −9‰) display a wide range of $\delta^{18}O$ values (−6‰ to −2.3‰), which may reflect differences in the vegetation water sources rather than dietary changes.

When considered together with the strontium data –indicating that most animals were local in terms of site (mobility scale "a" in this study) although some grazed in geologically distinct areas (intra-island operational mobility scale)- these results suggest that herds may have exploited pastures characterized by different microclimates while remaining largely within the same geological framework at the island scale. However, given the limited sampling resolution and the lack of sequential analyses, this interpretation should be regarded as provisional. At present, the available data are compatible with local grazing practices, but they do not allow a definitive distinction between short-range mobility, seasonal movements, or other forms of animal management at the intra-island scale.

5. Conclusions

This study presents the first isotopic analysis of livestock from a Menorcan *taula* sanctuary. This analysis sheds new light on local herd management and ritual practices during the Late Iron Age. The study of the *taula* enclosure at Binissafullet reveals a clear contrast between the diversity of imported materials and the local origin of the animals used in rituals. While ceramics from various parts of the Mediterranean were found in the structure the results of the zooarchaeological study suggest a local origin of the animals consumed (Valenzuela, 2021a). Isotopic analyses ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) of 27 individuals indicate that most animals were raised locally, within the same area or broader geological framework (in this study mobility scale type a). Nevertheless, a small number of outliers can be identified. These caprines, including both sheep and goats, display strontium values compatible with grazing in more radiogenic areas of Menorca (mobility scale type b in this study), potentially corresponding to the northern region of the island (Tramuntana), located approximately 8 km from the site. Within the current interpretative framework, this pattern may reflect limited short-range movements across neighbouring exploitation areas, rather than systematic long-distance mobility (Riudavets and Ferrer, 2022). Similar patterns of predominantly local herding combined with occasional intra-island movements have been suggested for other Bronze and Iron Age contexts in Menorca (Valenzuela-Suau et al. 2021; Valenzuela, 2023).

Carbon isotope ($\delta^{13}C$) results are consistent with a diet based on C_3 vegetation typical of the Mediterranean environments, with no significant differences between species. In this context, variability observed in oxygen isotope values ($\delta^{18}O$) is more likely related to seasonal or micro-environmental factors. A subset of individuals exhibits relatively enriched $\delta^{13}C$ values that do not show clear correlation with $\delta^{18}O$. At present, the consumption of seaweed or C_4 plants can be reasonably exluded (Pérez-Jordà et al. 2018; Balasse et al. 2019). Instead, increased water stress affecting C_3 plants represents the most parsimonious explanation, in agreement with paleoenvironmental and archaeological evidence pointing to a dry deforested and anthropized landscape in prehistoric Menorca (Picornell-Gelabert, 2012; Portillo et al., 2014; Anglada et al., 2013; Picornell-Gelabert and Servera-Vives, 2017; Picornell-Gelabert and Carrión, 2017; Pérez et al., 2017; Servera-Vives and Currás, 2016; 2017; Servera-Vives and Riera, 2024; Valenzuela-Suau et al. 2022b).

Overall, the isotopic data indicate largely consistent diet and predominantly local herd management at the Binissafullet *taula* enclosure. Most strontium isotope values fall within the same broad geological framework, although a small number of individuals display signatures compatible with grazing in geologically distinct areas at the intraisland scale. At the same time, the lack of sequential analyses, the absence of a comprehensive bioavailable strontium isoscape for the Balearic Islands, and the limited baseline resolution currently available prevent more precise interpretations regarding the timing, extent, or regularity of animal movements.

Taken together, the evidence is best understood as reflecting mainly local herding practices, potentially combined with limited short-range mobility within Menorca (intra-island scale), rather than systematic or large-scale movement between different geological zones (operational mobility scales c and d in this study). In parallel, the presence of imported ceramics indicates that non-local materials were incorporated into ritual contexts that were otherwise based on local resources, although the processes through which these goods circulated remain unclear (see e.g. Ramon, 2017).

This study adopts a multiproxy approach to explore herding catchment areas and animal diet at a *taula* sanctuary. However, given that only one sample per individual was analysed and seasonal mobility cannot be directly assessed, future research based on sequential isotopic sampling and a high-resolution regional isoscape will be essential to further test and refine these interpretations.

CRediT authorship contribution statement

Lua Valenzuela-Suau: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alejandro Valenzuela:** Writing – review & editing, Validation, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Antonio Delgado:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Leopoldo D. Pena:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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