Journal of Archaeological Science: Reports 62 (2025) 105035

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Territorialisation and human mobility during the Iron Age in NE Iberia: An approach through Isotope Analyses of the Severed Heads from Puig Castellar (Barcelona, Spain) and Ullastret (Girona, Spain)

Rubén de la Fuente-Seoane [a,*], Diego López-Onaindia [b,c], Ferran Codina Falgas [d], Gabriel De Prado [e], Conxita Ferrer Álvarez [f], M. Carme Rovira Hortalà [g], Marta Díaz-Zorita Bonilla [h], Ariadna Nieto-Espinet [i], M. Eulàlia Subirà [a]

[a] *Unitat d'Antropologia Biològica, Departament de Biología Animal, Biología Vegetal i Ecología, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, Spain*
[b] *Université de Bordeaux, UMR-5199 PACEA, Bâtiment B8, Allée Geoffroy Saint Hilaire 33615, Pessac Cedex, France*
[c] *Aranzadi Zientzia Elkartea/Sociedad de Ciencias Aranzadi, Zorroagagaina 11, 20014 Donostia-San Sebastián, Spain*
[d] *Serveis Territorials, Departament de Cultura, Generalitat de Catalunya, Girona, Spain*
[e] *Museu d'Arqueologia de Catalunya (MAC), Ullastret, Spain*
[f] *Puig Castellar - Museu Torre Balldovina, Santa Coloma de Gramenet, Spain*
[g] *Museu d'Arqueologia de Catalunya (MAC), Barcelona, Spain*
[h] *Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, University of Tübingen, Burgsteige 11, 72070 Tübingen, Germany*
[i] *Grup d'Investigació Prehistòrica (GIP), Departament de Geografía, Història i Història de l'Art, Universitat de Lleida, 25003 Lleida, Spain*

A R T I C L E I N F O

Keywords:
Isotope analyses
Human mobility
Severed heads, Territoriality
Violence
Iberian peninsula
Iron age

A B S T R A C T

During the late 1st millennium BCE, the societies from northeastern Iberia underwent rapid transformations due to their interaction with Mediterranean networks. The archaeological record reflects a widespread process of territorialisation and the emergence of social inequalities. However, the generalisation of cremation as the funerary practice makes more difficult to reconstruct the biological characteristics and social structure of these communities.

The severed heads represent a unique symbolic practice within the Iberian world and offer an exceptional opportunity to analyse these communities. It has been proposed that they might have been protective relics from ancestors or war trophies of foreign enemies. But these hypotheses have not been tested yet, nor has the relationship of these groups with their territory.

This paper provides new data to understand how interactions between human communities linked to the NE Iberian territory were articulated. This has been possible thanks to the analysis of seven severed skulls from two major sites: Ullastret and Puig Castellar. This was performed using a multiproxy approach combining bioarchaeology with $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ stable isotope analyses. The integration of anthropological, isotopic, and archaeozoological data, along with local baselines of bioavailable strontium values has provided valuable information about the degree of connectivity between territories, and the impact of sociopolitical context system on human and animal mobility in local Iron Age societies.

1. Introduction

From the 6th century BCE onwards, the Iberian Northeast (NE) is characterized by incipient processes of territorialization and violence among communities. These processes are evidenced in the archaeological record through significant changes in land occupation systems, the emergence and proliferation of fortified settlements, changes and complexification in urbanism and the increase in Mediterranean-origin imported objects. For example, the presence of weapons in tombs, as well as the evidence of public displays in certain

* Corresponding author.
E-mail addresses: ruben.delafuente@uab.cat (R. de la Fuente-Seoane), diego.lopez-onaindia@u-bordeaux.fr (D. López-Onaindia), ferrancodina@gencat.cat (F. Codina Falgas), gdeprado@gencat.cat (G. De Prado), cferreralvarez@gmail.com (C.F. Álvarez), crovirah@gencat.cat (M.C. Rovira Hortalà), marta.diaz-zorita-bonilla@uni-tuebingen.de (M. Díaz-Zorita Bonilla), ariadna.nieto@udl.cat (A. Nieto-Espinet), eulalia.subira@uab.cat (M.E. Subirà).

https://doi.org/10.1016/j.jasrep.2025.105035
Received 6 November 2024; Received in revised form 30 January 2025; Accepted 6 February 2025
Available online 13 February 2025
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buildings and non-surviving injuries provide insights into these conflicts (Agustí and Martín, 2006; Fernández-Crespo et al., 2020; Guzmán et al., 2018; Rovira Hortalà, 2005; Sanmartí, 2003). These elements related to the material culture highlighted the consolidation of processes of hierarchization through social coercion initiated during the Early Iron Age and crystallized, at this time, into what has been called the Iberian culture (p.e: Aranegui Gascó, 1998; Asensio and Jornet, 2019; Asensio-Vilaró, 2019; Cachero, 2007; Gailledrat, 2014; Junyent, 2015; Sanmartí, 2009a; Sanmartí and Belarte, 2001; Sanmartí and Santacana, 2005).

The Iberian culture developed between the 6th and the 1st centuries BCE along the Mediterranean coast (Fig. 1) between the current eastern Andalusia (Iberian peninsula) and western Languedoc (France) including also, inland the south-eastern areas of the Iberian Plateau and the Ebro river basin to the current Aragon region (e.g: Gailledrat, 2014; Sanmartí and Santacana, 2005).

These societies emerged rapidly as indigenous populations underwent significant evolution due to various factors, especially their contact with Mediterranean networks, particularly with Phoenician and Greek societies (Asensio-Vilaró, 2019; Sanmartí, 2009a).

These interactions favoured the emergence of local aristocracies, which consolidated a society based on social inequalities and strong hierarchy (Asensio Vilaró et al., 2001b; Sanmartí, 2009a; Sanmartí et al., 2015). This system was supported by the administrative centralization of power, ensuring the accumulation and redistribution of agricultural surplus (Asensio Vilaró et al., 2002; Prats Ferrando, 2017) and livestock resources (Colominas Barberà, 2013; Nieto-Espinet et al., 2021; Valenzuela-Lamas et al., 2018), the redistribution of colonial prestige goods (Belarte Franco et al., 2020; Sanmartí, 2014), and control over access to land and communication routes with the Mediterranean.

The territorial and administrative organization of these societies is structured around some urban centres that hold power and organize the settlement structure. Between the 6th and 5th century BCE, a hierarchical system of occupation was implemented and organized into several centralized political units. There was a greater diversification in settlement types: central places with fortifications (>3 ha in size), peripheral mid-rank settlements (3–1.5 ha), and small-sized scattered settlements (Asensio Vilaró et al., 1998; Sanmartí and Santacana, 2005). We also have military settlements specialized exclusively in territorial control (Asensio Vilaró et al., 2002, 2001a). At this point, coercion would be used as a means of control in a strongly territorialized context.

From the 4th century onwards, there was significant growth of some settlements that became large urban centres (over 10 ha in size). The escalation in production systems is attributed to both internal factors, such as population growth, and external influences, including colonial trade (Asensio Vilaró et al., 2002). The intensification processes promoted the consolidation of an administrative system managed by political entities with a larger territorial influence during the 3rd century BCE. The estimated areas covered by these territories vary between 2000 to 2800 km^2 (Sanmartí and Santacana, 2005). This new scenario was characterized by a higher degree of specialization and hierarchization of settlements, and the existence of an Iberian coinage, weight, and writing system. These developments are thought to reflect the emergence of a proto-state political framework, encompassing diverse ethnic groups (Junyent, 2015; Sanmartí, 2004; Sanmartí and Belarte, 2001).

There is abundant literature focused on the analysis of different elements of material culture, which has allowed for a comprehensive overview of the economic and cultural dynamics of Iberian societies in NE Iberia. However, this reality contrasts with the inherent limitations of the anthropological record for this period. Cremation was the predominant burial ritual during this period, which poses challenges for studying the human remains (Agustí, 2001; Barroso, 1993; Subirà et al., 2011). Consequently, little is known about the biological characteristics

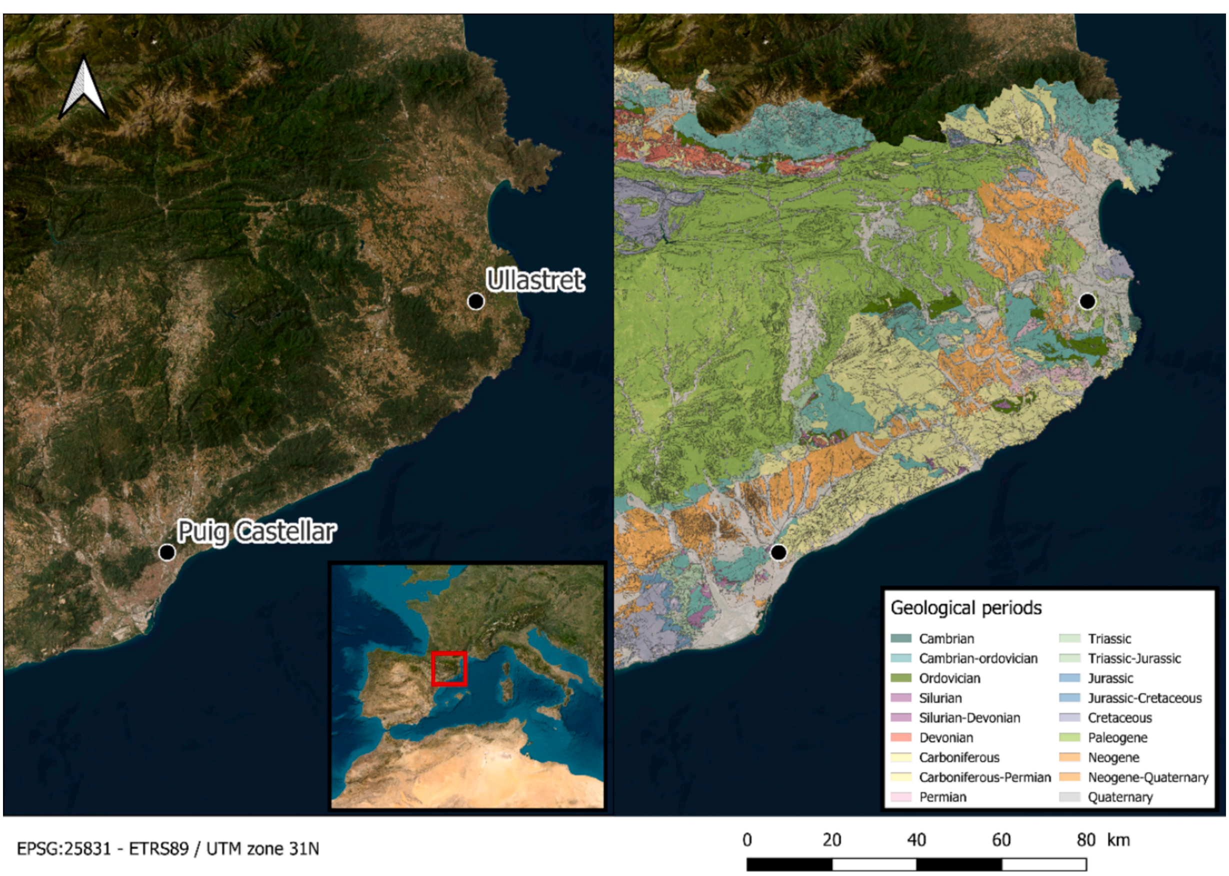

Fig. 1. Figure representing the locations (left) of the sites presented in this work: Puig Castellar (Santa Coloma de Gramenet, Barcelona) and Ullastret (Ullastret, Girona). On the right side: the NE Iberia geological formations (right) by geological period are also plotted.

and geographical origins of these populations.

The funerary practices and the treatment of the bodies have been suggested as indicators of hierarchic position and population organisation markers in certain groups (Sanmartí, 2009b). Few individuals were treated differently by these local populations: a few elite warriors in funerary context (Belarte Franco et al., 2020; Graells i Fabregat, 2007; Sanmartí and Santacana, 2005) and some perinate individuals in domestic contexts (Aranegui Gascó, 2015; Sanmartí, 2009a; Sanmartí and Santacana, 2005). Some of the rare human remains recovered in archaeological contexts in the northeast of the Iberian peninsula are, precisely, the severed heads, which are the central focus of this paper.

This work provides new data to better understand how interactions between human communities linked to the territory of northeastern Iberia were articulated during a period marked by intense local territorialization, but also with a need for openness towards Mediterranean cultures. The integrated study of mobility patterns and geographical origin of these individuals will provide key information about the social relations and degree of circulation of human communities, as well as the level of connectivity between territories during the Iron Age.

1.1. The practice of "severed heads" in NE Iberia

There are Greco-Latin texts recording the extensively practice of severed heads, explicitly referring to the Gallia; however, there are very few archaeological records of this practice – defined as a tokenisation of the head –, with vague or not very explanatory references (Ciesielski et al., 2011; De Prado and Rovira Hortalà, 2015; Subirà and Rovira Hortalà, 2019).

In NE Iberia this practice was first documented by Ferran de Sagarra in 1904 (Sagarra i de Siscar, 1906a, 1906b) at the Puig Castellar site (Santa Coloma de Gramenet, Barcelona). The term "severed heads" (têtes coupées in French), in the bibliography of the Iberian Peninsula (and especially that of Catalonia) corresponds to the term "nailed heads" or " embedded heads". In this work we will use the terminology "severed heads", because not all the documented cases involve the nailing of the head (Subirà and Rovira Hortalà, 2019).

There is evidence of this practice in the Iberian peninsula since the Bronze Age (Agustí et al., 2015). Nevertheless, this type of practice spread during the Iron Age, and has had different interpretations. These proposals range from its use either as protective relics (venerated individuals or ancestors) to elements of war prestige (enemies or members of other Iberian communities) (Agustí and Martín, 2006; Campillo, 1976; Campillo and Agustí, 2005; Subirà and Rovira Hortalà, 2019).

Their potential symbolic significance might have led to the display and exhibition of these severed heads for the community or in a designated area for a specific group. This exhibition would function as a demonstration of prestige and/or coercion. Previous studies developed a categorization of these skulls based on their location and context of appearance. Primarily, three main groups have been established: 1. skulls exhibited on the walls of houses, interpreted as belonging to enemies or individuals who faced punishment; 2. those discovered within storage pits, interpreted as offerings; and 3. those found within domestic spaces, interpreted as belonging to the most important enemies (Ciesielski et al., 2011; Oliver Foix, 1995).

Although usually the southern limit of this phenomenon would be considered around the Besós River (Barcelona), right at the settlement of Puig Castellar. The archaeological record indicates a significant number of these finds found mainly around the Gulf of Lion (Agustí and Martín, 2006; Subirà and Rovira Hortalà, 2019). Lately, this border has shifted further south, thanks to the discovery of a skull with these characteristics in the Iberian settlement of Olèrdola (Alt Penedés region, Barcelona) (Molist and Principal, 2022).

Some severed skulls have been found in the NE of the Iberian peninsula, specifically documented near the site of Puig Castellar, in Ca n'Olivé (Cerdanyola del Vallés, Barcelona) and in the settlements of Burriac (Badalona, Barcelona) and Turó de Montgat (Montgat, Barcelona) (De Prado and Rovira Hortalà, 2015; Rovira Hortalà and Subirà, 2023). In the case of the last two, their nature slightly differs, as no evidence of drilling or nailing has been found. There are also some cases of collected heads in sites of eastern Spain, but without apparent perforation (De Prado and Rovira Hortalà, 2015; Oliver Foix, 1995).

In Ullastret, the anthropological analyses have allowed us to observe a tissue treatment, prior to the nailing of these skulls to the place of exhibition. In the archaeological excavations conducted in 2012, some soil in contact with the discovered skulls was analysed to determine the presence of residues related to possible treatments used on the skulls, such as cedar oil. Ribas and his collaborators performed several analyses but found no evidence of such substances (Agustí et al., 2016; Ribas et al., 2014). Despite this result, the treatment observed in some skulls, which included some incisions to prepare the skull before its exhibition (Agustí et al., 2016; Subirà and Rovira Hortalà, 2019), leads us to believe in the existence of specialists or individuals with specific knowledge of the techniques for this preparation. Therefore, we think it was an activity carried out with some regularity (Agustí et al., 2016, 2015; Agustí and Martín, 2006; Ciesielski et al., 2011; Subirà and Rovira Hortalà, 2019).

It is important to consider who the protagonists of this practice were and what motivated its enforcement. This research builds upon several previous studies that focused primarily on anthropological analyses (Agustí and Díaz-Carvajal, 2015; Agustí and Martín, 2006; De Prado and Rovira Hortalà, 2015; Subirà and Rovira Hortalà, 2019). Undoubtedly, it was a symbolic and ideological practice and, as we have previously suggested, possibly conducted as a form of coercion against groups seeking to challenge the established order of these societies. Therefore, several questions arise from these severed heads. Were they inhabitants of the settlement? Were they the result of repression? Or were they trophies from conflicts with other groups?

2. Materials and methods

2.1. Archaeological sites included in the study

2.1.1. Puig Castellar

The Iberian settlement of Puig Castellar (5th – 3rd/2nd century BCE) in Santa Coloma de Gramenet (Barcelona, Spain), is situated on top of a hill known as *Turó del Pollo* within the *Serralada de Marina* (Fig. 1).The *Serralada de Marina* is a narrow section of the *Serralada Litoral Catalana* primarily consisting of metamorphic and magmatic materials. The prominent geological units (GU) in this region include Cambro-Ordovician and Ordovician micaceous and sandy shales, as well as granodiorites, alkaline granites, and acid porphyries dating back to the Carboniferous-Permian period.

The geographical location provides a wide range of visibility over the estuary of the Besós river, the Barcelona plain and a large part of the Vallès and Maresme regions. It can also be seen from other points occupied in the Iberian period, such as the hill of Montjuïc (Barcelona), the Hill of la Rovira (Barcelona), the hill of Mas Boscà (Badalona), the hill of Montgat or the hill of Les Maleses (Sant Fost de Campsentelles). These were privileged conditions from a strategic point of view, both in terms of control of the territory and the possible defence of the cultivation and farming areas.

Puig Castellar was a site of the *laietani* and a nucleus designed for territorial control, although this does not exclude the development of other economic and productive activities (Ferrer and Rigo, 2003; Sanmartí, 1992). This can be attributed to its advantageous location, which allowed it to oversee the passage from the coast to the inland areas along the Besòs river. Agricultural tools (millstones and iron tools) were found, suggesting that some degree of food processing and subsistence activities took place at the site (Belarte, 2013; Ferrer and Rigo, 2003). This role is even more evident if we consider the existence of a large number of rural establishments scattered around the area, a good example of which is the Can Calvet site, located at the foot of the hill. This site, located at the foot of Puig Castellar, exhibits functions related to agrarian exploitation (Asensio Vilaró et al., 2001a, 1998; Sanmartí, 1992; Zamora Moreno et al., 2001).

From an urban planning perspective (Fig. 2), Puig Castellar itself is relatively small, despite a notable accumulation of buildings. It covers a surface area slightly over 4000 m^2 and features fortifications adapted to the hill topography. These enclosures generally consist of single-room structures, with a few exceptional multi-roomed buildings, likely indicative of social status differences (Belarte, 2013).

The presence of weaponry suggests the existence of a group specialised in either military or violent activities (Ferrer & Rigo, 2003).

Although imported objects and goods found at Puig Castellar are scarce (Asensio Vilaró, 2019), based on the discovery of imported pottery from the 7th and 6th centuries BCE, it is thought that the site was occupied before the first half of the 5th century BCE. The fortified nucleus would have then been in use from the end of the 4th century BCE until the end of the 3rd century BCE or the beginning of the 2nd century BCE (Ferrer and Rigo, 2003).

The settlement of Puig Castellar was abruptly abandoned around 200 BCE, a timeframe that aligns with the Second Punic War and Cato's military campaigns. This sudden abandonment strongly indicates a direct connection to the Roman invasion of the Iberian Peninsula (Asensio-Vilaró, 2019).

2.1.2. *The Iberian Town of Ullastret*

Ullastret, located in the Baix Empordà region (Girona, Spain), is presently recognized as the largest known Iberian site in Catalonia (Fig. 1). The archaeological complex encompasses two sites, namely Puig de Sant Andreu and Illa d'en Reixac.

Over time, the Baix Empordà plain has been shaped by the deposition of alluvial sediments carried by the Ter and Daró rivers. The geological composition of the area primarily consists of clays interspersed with conglomerates and grey sandstones from the Eocene-Oligocene period. Additionally, there are clays, silts, and sands originating from the Lower Bartonian to Lower Priabonian periods. The region also contains clays and marshy sands from the Pleistocene era, as well as sandstones and limestones from the Bartonian period. Lastly, the area includes the Ter alluvial and/or deltaic plain from the upper Holocene, along with alluvial-colluvial deposits consisting of gravels with a sandy and argillaceous matrix from the Holocene.

From the 4th century BCE onwards, Ullastret developed into an urban complex spanning approximately 15 ha. This served as the "capital" of the *Indigetes* territory, exerting control over the region extending from the Tordera River in the south to the Albera massif in the north (Agustí et al., 2015).

In terms of territorial significance, Ullastret formed part of a network of settlements in the area, of which it was the central hub (Plana Mallart and Martín Ortega, 2003). Furthermore, survey campaigns have revealed the scattered distribution of settlements surrounding the Puig de Sant Andreu site. These smaller settlements were likely specialized in the production of artefacts and the extraction of raw materials (Plana Mallart and Martín Ortega, 2001).

Ullastret was established during the 7th to 6th centuries BCE by local groups (Cebrián Martínez, 2018; De Prado and Rovira Hortalà, 2015). This settlement showcases various structures, including water channels designed to redirect rainwater into planned reservoirs for storage purposes. Researchers have drawn architectural similaritiesbetween these water systems and those found in the nearby settlement of Empúries, suggesting a potential relationship and contact between the two settlements (De Prado and Rovira Hortalà, 2015; Olmos Benllonch, 2008). The defensive system of Ullastret is also noteworthy, as well as the urban layout, which features a mix of structures classified as domestic and unique buildings, some of which are considered aristocratic (Codina et al., 2017, 2012).

Research conducted at Ullastret have revealed a significant number of structures interpreted as residential buildings with an aristocratic status, along with several shrines located at the hilltop (Codina et al., 2012). These findings support the consensus among scholars that Ullastret was part of a group of prominent oppida, classified as first-order settlements, which exerted political and territorial control over

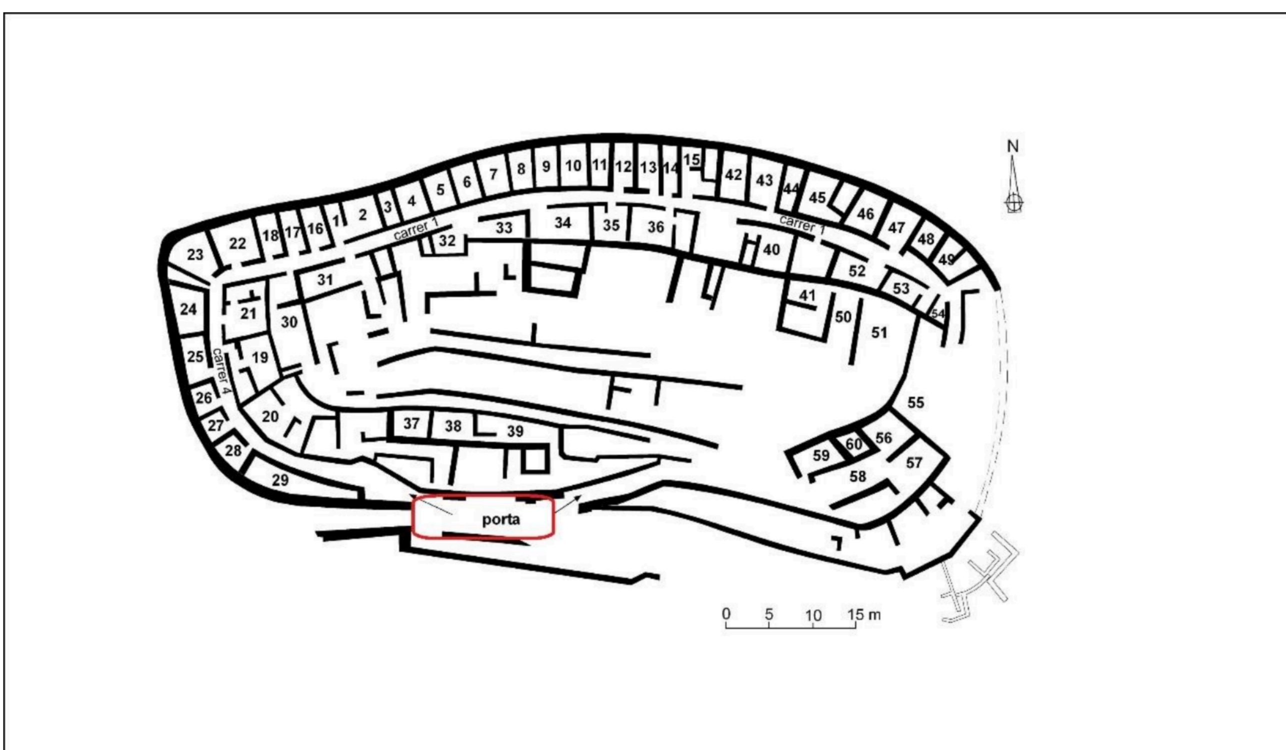

Fig. 2. Plan of Puig Castellar. The area marked by the red rectangle is where the skulls were found. Author: Conxita Ferrer Àlvarez.

the Indigetes region (Agustí et al., 2016; Asensio-Vilaró, 2019; Plana Mallart and Martín Ortega, 2003).

Considering the presence of silo fields and the characteristics shared with other elevated oppida, it is highly probable that the primary activity of Ullastret, alongside its political and territorial management, was cereal production. Also, Ullastret's smaller neighbouring settlements are typically associated with agriculturally rich environments (Plana Mallart and Martín Ortega, 2001).

The decline and abandonment of Ullastret occurred towards the end of the 3rd century or the beginning of the 2nd century BCE, likely connected to the conclusion of the Second Punic War and the arrival of the Romans in the Iberian peninsula (De Prado and Rovira Hortalà, 2015).

2.2. Archaeological samples

In this study, we extracted enamel from 7 severed human heads, 4 from Puig Castellar and 3 from Ullastret (Table 1). Additionally, we analysed teeth from various faunal individuals to compare their results with those of humans. The samples include 1 domestic dog (Canis familiaris), 2 caprines, 2 cattle, and 3 pigs from the archaeological excavations at Puig Castellar (n = 8). From Ullastret, we analysed 3 caprines, 3 cattle, and 4 pigs (n = 10). (S2, Table 1). The scarcity in the number of individuals analysed for mobility is explained by the smaller number of teeth recovered.

The human remains from Puig Castellar (Table 1) included in the present work (Table 1; see Supplementary Material S2) were found in the early 20th-century campaigns led by Ferran de Sagarra i de Císcar (Sagarra i de Siscar, 1906a, 1906b). These individuals were found near the inner face of the wall, beyond the main entrance of the settlement (Fig. 2), suggesting an interest in making these remains visible (Agustí and Martín, 2006; De Prado and Rovira Hortalà, 2015; Rovira Hortalà, 1999, 1998; Subirà and Rovira Hortalà, 2019). These individuals were previously analysed and described by two of the current authors following the methods described in Campillo & Subirà (2004) (Subirà & Rovira Hortalà, 2019). The faunal remains analysed in this work, were located near the human skulls, close to the main entrance of the site.

The human remains from Ullastret included in this work (Table 1) were found during different campaigns and in different locations on the site (Fig. 3). ULL_HU1 was found in zone 13 during the 2003 excavation. ULL_HU2 was found in a ditch near the wall during the excavation campaigns between 1964 and 1969, but it is unclear whether it was found in the 146 or 106 silo (Campillo, 1976; Pujol Puigvehí, 1980). ULL_HU3 was found in 1996 in zone 14. These remains have been described and published in various sources (Agustí et al., 2015; Agustí and Díaz-Carvajal, 2015; Agustí and Martín, 2006; Agustí et al., 2016; Campillo, 1976; De Prado and Rovira Hortalà, 2015; Pujol Puigvehí, 1980; De Prado and Rovira Hortalà, 2015). Finally, the faunal remains were discovered in 2012 between zones 152 and 153.

Table 1
Sample information from human samples from Puig Castellar and Ullastret. Mineralisation data come from AlQahtani et al., 2010.

Puig Castellar				
Individual	Sex	Age	Tooth	Mineralisation
PC_HU1	Undeterminate	15	M_2	2.5y – 8.5y
PC_HU2	Male	18–25	P_1	2.5y – 6.5y
PC_HU3	Male	25–35	P_2	2.5y – 6.5y
PC_HU4	Male	18–25	M_3	8.5y – 15.5y

Ullastret				
Individual	Sex	Age	Tooth	Mineralisation
ULL_HU1	Male	20–25	M^3	8.5y – 15.5y
ULL_HU2	Male	20–30	M_3	8.5y – 15.5y
ULL_HU3	Undeterminate	17–25	M_1	4.5 m – 2.5y

2.3. Bioavailable strontium (BASr) samples

To obtain local BASr baseline data we sampled 40 soil and vegetation samples from 9 different geological units around Puig Castellar and Ullastret, within a 2 km radius of each site. Specifically, we collected 5 soil samples from Puig Castellar and 7 from Ullastret (see Fig. 4). Vegetation samples, comprising both short-rooted and long-rooted species, were gathered from 13 locations at Puig Castellar and 14 at Ullastret. In the laboratory, 8 vegetation samples from each site were consolidated into 4 samples each, due to time constraints, as they originated from the same geological unit (see Table 2 for details).

2.4. Palaeomobility analysis

To investigate the mobility patterns of the population, we conducted $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ isotope analyses. Strontium (Sr) has multiple stable isotopes. While $\delta\ ^{87}Sr$ is also stable, it is derived from the decay of rubidium-87 (^{87}Rb) and its relative abundance compared to total strontium is influenced by the amount of $\delta\ ^{87}Rb$ present in the rock and its geological age (Bentley, 2006; Dickin, 1995; Diez-Fernández, 2019; Faure, 1977; Price et al., 2002). As a result, each geological site exhibits a unique composition for this isotope.

Radiogenic strontium isotopes are transferred from the geological substrate to animals and plants through the food chain, replacing calcium in the formation of hydroxyapatite in bones and teeth (Carames-Pasaron et al., 2012; Hoppe et al., 2003). Consequently, strontium becomes incorporated into dental enamel and bones through dietary intake. Tooth enamel, once formed during childhood, remains unchanged and reflects the geological composition of the location where it developed. $^{87}Sr/^{86}Sr$ is subject to little isotopic fractionation as a result of biological processes and its isotopic signal is directly incorporated into tooth enamel during mineralisation, mainly through water and plants ingested by the individual (Beard and Johnson, 2000; Ericson, 1985; Price et al., 2002). The strontium isotope compositions of the bioapatite thus reflect the signatures of the geological area where the individual resided and fed during the process of dental enamel mineralisation (Beard and Johnson, 2000; Madgwick et al., 2012; Price et al., 2002).

Oxygen isotopes are absorbed by individuals through liquid consumption, and their analysis can be applied to mobility studies. One approach is to examine the ratio of ^{16}O to ^{18}O, which varies due to the differential evaporation and precipitation of molecules containing these isotopes. Lighter isotopes, such as ^{16}O, evaporate more easily and are less likely to be present in precipitation compared to heavier isotopes like ^{18}O. Variables such as distance from the coast, altitude, latitude and climate influence the isotope ratio, while the temperature of water molecules affects oxygen isotopic fractionation (Bryant and Froelich, 1995; Daux et al., 2008; Kohn, 1996; Longinelli, 1984; Luz et al., 1984; Podlesak et al., 2008).

In our study, we used $\delta^{18}O$ analysis as an additional proxy to complement the $^{87}Sr/^{86}Sr$ ratio results. Since stable oxygen isotopes fractionate as they move through different environments and make it challenging to directly compare $\delta^{18}O$ values from different variables (Dahlstedt et al., 2021; Longinelli, 1984; Luz et al., 1984), we did not employ bioavailable oxygen to establish a local range.

The analyses of the tooth enamel samples were carried out at the Laboratory for Isotopic and Bioarchaeological Research at the University of Tübingen and then at the Curt-Engelhorn-Zentrum Archäometrie gGmbH in Manheim, and the sediment and vegetation samples were analysed in the Advanced Research Facilities (SGIker) at the University of the Basque Country-UPV/EHU.

All the vegetation and sediment samples were collected considering the geological unit to which they corresponded, information we obtained through the use of GIS software (geographic information system) combined with the geological units map of the ICGC (*Institut Cartogràfic i Geològic de Catalunya*), in order to establish the best areas for sampling.

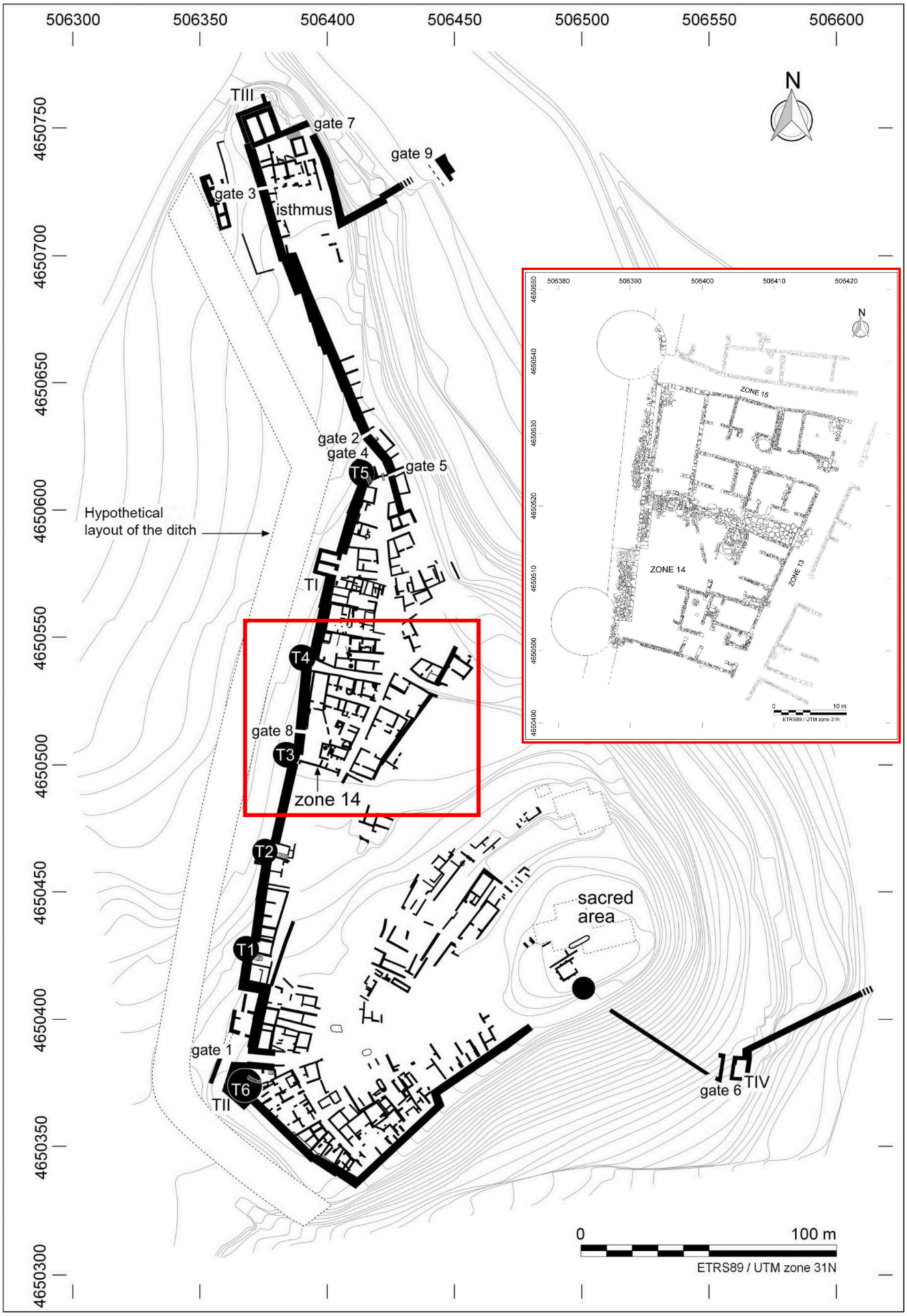

Fig. 3. Plan of the Puig de Sant Andreu site (modified from Fig. 5 and Fig. 11, chapter 3, in Garcia-Garcia et al., 2016).

The logistical conditions in which the surveys were carried out and the recurrent modification of the survey points due to the high degree of anthropization of these areas forced us to delimit a much smaller area (<2km) than originally planned (<5km).

The tooth enamel samples were photographed and then mechanically cleaned by abrasion using a Dremel Minimite-750 cordless drill of variable Speed MultiPro drill equipped with an engraving cutter. This removed any adhering organic matter or contaminants, as well as the outermost layers of tooth, which are the most susceptible to diagenetic contamination (Blank et al., 2018; Knipper et al., 2014, 2012;

Fig. 4. Locations where samples were gathered for the analysis of bioavailable strontium around the Puig Castellar and Ullastret sites. The base map is the 1:50000 geological map of the Cartographic and Geological Institute of Catalonia (ICGC) plotted by geological periods.

Maurer et al., 2012). Afterwards, 12 mg of tooth enamel were dissolved in 0.50 mL of 3 N HNO_3 for each enamel sample. The strontium was separated from the sample matrix using EiChrom SrSpec resin, a crown-ether strontium-selective resin (100–150 μm diameter) loaded into the tip of a glass column. The dissolved sample was loaded in 250 μL of 5 M HNO_3, washed in 500 μL of 5 M HNO_3, and then the strontium was eluted with 1000 μL of H_2O.

The samples were analysed using the Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). Recent $^{87}Sr/^{86}Sr$ analyses of strontium carbonate standard SRM-987 yield a

Table 2
Information on BASr samples, including vegetation and soil samples from Puig Castellar and Ullastret.

Puig Castellar				**Ullastret**			
Code	Sample type	GU	Period	Code	Sample type	GU	Period
L-PC01	Long-rooted	ÇOrP	Cambro-Ordovician	L-ULL01	Soil	Peg	Paleogene
	Long-rooted	ÇOrP	Cambro-Ordovician	L-ULL02	Soil	PElg	Paleogene
	Long-rooted	ÇOrP	Cambro-Ordovician	L-ULL03	Soil	PElg	Paleogene
	Long-rooted	ÇOrP	Cambro-Ordovician	L-ULL04	Long-rooted	Peg	Paleogene
	Long-rooted	ÇOrP	Cambro-Ordovician	L-ULL05	Soil	T_Qpa	Quaternary
L-PC02	Soil	ÇOrP	Cambro-Ordovician	L-ULL06	Soil	Qpc	Quaternary
	Soil	ÇOrP	Cambro-Ordovician	L-ULL07	Soil	Qac	Quaternary
L-PC03	Soil	Ggd	Carboniferous-Permian	L-ULL08	Soil	PEOa	Paleogene
L-PC04	Long-rooted	Ggd	Carboniferous-Permian	L-ULL09	Long-rooted	PElg	Paleogene
L-PC05	Soil	Gpg	Carboniferous-Permian		Long-rooted	PElg	Paleogene
L-PC06	Soil	Ggd	Carboniferous-Permian	L-ULL10	Long-rooted	T_Qpa	Quaternary
L-PC07	Long-rooted	Gpg	Carboniferous-Permian	L-ULL11	Long-rooted	Qpc	Quaternary
L-PC08	Long-rooted	Ggd	Carboniferous-Permian	L-ULL12	Long-rooted	Qac	Quaternary
L-PC09	Short-rooted	ÇOrP	Cambro-Ordovician	L-ULL13	Long-rooted	PEOa	Paleogene
	Short-rooted	ÇOrP	Cambro-Ordovician	L-ULL14	Short-rooted	Peg	Paleogene
L-PC10	Short-rooted	Ggd	Carboniferous-Permian	L-ULL15	Short-rooted	PElg	Paleogene
L-PC11	Short-rooted	Gpg	Carboniferous-Permian		Short-rooted	PElg	Paleogene
L-PC12	Short-rooted	Ggd	Carboniferous-Permian	L-ULL16	Short-rooted	T_Qpa	Quaternary
				L-ULL17	Short-rooted	Qpc	Quaternary
				L-ULL18	Short-rooted	Qac	Quaternary
				L-ULL19	Short-rooted	PEOa	Paleogene

value of $^{87}Sr/^{86}Sr = 0.710261 \pm 0.000020$ (2σ), which is in agreement with analyses of SRM-987 using a thermal ionization mass spectrometer (TIMS), where $^{87}Sr/^{86}Sr = 0.710263 \pm 0.000016$ (2σ) (Stein et al., 1997), and analyses of SRM-987 using an identical MC-ICP-MS, where $^{87}Sr/^{86}Sr = 0.710251 \pm 0.000006$ (2σ) (Balcaen et al., 2005).

The soil samples were dried overnight at 50 °C and then sieved through a 2 mm sieve. Then an aliquot of 1 g of soil was leached with 2.5 mL of ammonium nitrate (NH_4NO_3) in an orbital shaker for 8 h. Samples were then centrifuged at 4000 rpm for 15 min and the supernatant liquid was evaporated, and the traces of soluble organic matter were dissolved with 2–3 drops of hydrogen peroxide. Once this process was completed, we proceeded to chromatography by loading the solutions into a column filled with a specific strontium resin (Sr-resin, Triskem International, Bruz, France) and acids of different concentrations (HNO_3 0.05 N and HNO_3 7 M) (Pin and Bassin, 1992).

The vegetation (trees and/or bushes) were placed in heat-resistant porcelain crucibles and incinerated in an oven at 550 °C for 1 night. An aliquot of 0.1 g of ash was dissolved with 1.5 mL of HNO_3 7 M. The dissolutions were filtered using Teflon filters of 0.2 µm of pore-size over the chromatographic columns filled with SrSpec resin to remove the carbon particles remaining after dissolution.

Sediment and vegetation samples were analysed using a Thermo Neptune MC-ICP-MS spectrometer at the SGIker of the University of the Basque Country/Euskal Herriko Unibertsitatea (Puente-Berdasco et al., 2022). The reliability and reproducibility of the method has been verified by measurements of the standard reference material NBS-987 at the beginning and the end of the analytical sessions. Employing the commonly used $^{88}Sr/^{86}Sr$ of 8.375209 for instrumental mass fractionation (Nier, 1938), the mean $^{87}Sr/^{86}Sr$ obtained for NBS-987 was 0.710284 +/- 0.000020 (n = 8).

For $\delta^{13}C$ and $\delta^{18}O$ values, samples were analysed at 70 °C using a ThermoFinnigan Gasbench II connected to a Finnigan Delta Plus XL CFIRMS at the University of Tübingen. Isotopic abundances are expressed as δ (delta) values in parts per mil (‰), as follows: $\delta^{13}C = (^{13}C/\ ^{12}Csample/\ ^{13}C/\ ^{12}Cstandard - 1) \times 1000$ and $\delta^{18}O = (^{18}O/\ ^{16}Osample/\ ^{18}O/\ ^{16}Ostandard - 1) \times 1000$. The standards are the marine carbonate V-PDB for carbon and oxygen and V-SMOW for oxygen. These samples were analysed using the FinniganMAT 262 Thermal Ionisation Mass Spectrometer (TIMS) located at the Isotope Geochemistry Group of the University of Tübingen.

3. Results

3.1. BASr isotopes in geological units from Puig Castellar and Ullastret

The results obtained from the analysis of the 40 sediment and vegetation samples collected from 9 different geological units from Puig Castellar and Ullastret (Fig. 5), show a higher variability in the bioavailable Sr values in the Puig Castellar area compared to those provided by Ullastret. Additionally, the latter presents much lower Sr values.

Looking at these values for each species of plant sampled in both sites together, we see that, while there is a difference between the long and short rooted samples, it seems that the main difference is the formative period of the geology (Fig. 6). The more recent periods (Palaeogene and Quaternary) display quite similar values while the older ones (Cambro-Ordovician and Carboniferous-Permian) show much more variability. Statistical tests show that there are significant differences in terms of the formative period (Kruskal-Wallis chi-squared = 20.376, df = 3, p-value = 0.0001) of the geology and no significant differences in terms of the type of sample (Kruskal-Wallis chi-squared = 1.0323, df = 2, p-value = 0.5968). These differences could be due to the radioactive decay of the strontium-bearing source rock itself, which in the case of the more recent rocks would come from the weathering of earlier rocks.

This trend observed in the data can be seen in Fig. 7, where the different types of samples are plotted by geological period, and in the oldest period there is a pronounced difference between the long-rooted samples and the sediment and short-rooted samples that can be seen. The long-rooted samples collected from the Cambro-Ordovician period were among those that were homogenised in a single sample (L-PC01) (see Supplementary Material S2, Table 2). The difference observed between those long-rooted samples and the rest of the Cambro-Ordovician samples could be related to this procedure, although the rest of the homogenised samples did not give such results.

3.2. Archaeological results

3.2.1. Puig Castellar

The analysis of $^{87}Sr/^{86}Sr$ was performed in four human individuals, including three males and one undetermined sex individual (Table 3). The age groups show a fairly young demographic dataset (between 15 and 35 years old). It seems that the juvenile individual from Puig

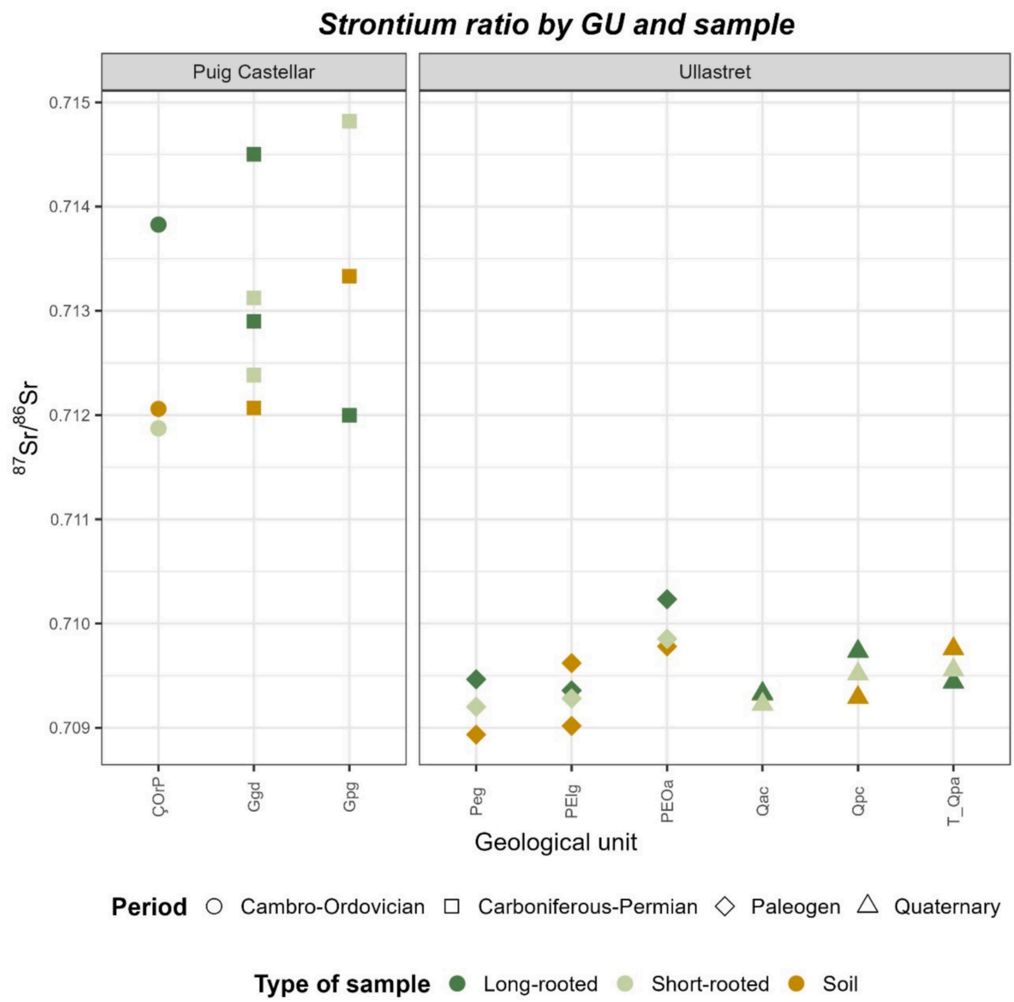

Fig. 5. Scatter plot showing the values of the $^{87}Sr/^{86}Sr$ ratio for the geological units analysed in this work, coloured by the source from which the values originate.

Castellar (PC_HU1) has higher radiogenic values than the rest of the adults. It should be noted, however, that the age reflected in the isotopic results are those corresponding to the moment of mineralisation of the tooth analysed (Table 3).

Concerning the $^{87}Sr/^{86}Sr$ ratios from the faunal remains (Table 3), there is a quite high degree of heterogeneity in the sample, as the samples range between 0.7083 and 0.7132, which is also observed in the $\delta^{18}O$ results ($\delta^{18}O_{VPDB}$ range: −0.55 ‰ to −6.15 ‰). We can see at a glance that, in the case of Puig Castellar, the human samples have lower strontium values than the archaeological faunal samples. The oxygen results provided different values for each species, however, the small sample size and the lack of oxygen values available for humans do not allow us to contract these results.

The range of variation in bioavailable strontium are between 0.7119 and 0.7148 (Table 4). To establish a baseline with greater certainty and ensure that the outliers do not overstate the sample, we decided to calculate a confidence interval for the local samples (soils and plants) from both sites. The confidence interval was set at the standard 95 %. In the case of Puig Castellar, this is between 0.7122 and 0.7136 (the dashed lines in Fig. 8).

If we contrast this range of human Sr isotopic values, we can observe that no individual from Puig Castellar is compatible with the local geology (<2km around the site) (Fig. 8). Only PC_CA1 (cattle), PC_SU2, and PC_SU3 (pig) are compatible with the local bioavailable strontium range. The absence of oxygen values in most humans is due to the small amount of enamel we were able to extract, and we decided to exploit the strontium results more significantly.

As the distribution of the local strontium sample is normal (Shapiro-Wilk test: W = 0.89768, p-value = 0.1731), we applied the Student one sample *t*-test to compare the local strontium means of Puig Castellar with the isotopic ratio of each human individual at the site (Table 5). Assuming that the locality will be characterized by a coincidence of means between each individual and the local isotopic signature, we can see that no human individual would be considered local.

The distribution of the fauna values is also normal (Shapiro-Wilk test: W = 0.93791, p-value = 0.5906) and if we overlap the information we have from the fauna with the local baseline strontium, we can observe that with the exception of individuals PC_CA1 (cattle), PC_SU2 and PC_SU3 (both suid), the rest of the samples would have a non-local origin (Fig. 8).

3.2.2. *Ullastret*

Concerning the Ullastret site, we have analysed the Sr isotopes of two male humans and one human of undetermined sex. As in Puig Castellar, we have a young individual (between 17–30 years old), and the older individual has provided a higher isotope ratio (Table 6). As mentioned in the previous case, however, our results reflect the time of mineralisation of the tooth analysed, not the time of death of these individuals.

The results of the local vegetation and soil samples define a range of variation of bioavailable strontium between 0.7089 and 0.7102 (Table 7 and the grey area in Fig. 9). When we compare this to the data we have on fauna and humans, we find that two human individuals (ULL_HU1 and ULL_HU3) fall within the local signal range (<2km), as well as cattle (ULL_CA1), pig (ULL_SU2) and two caprines (ULL_CP1 and ULL_CP2).

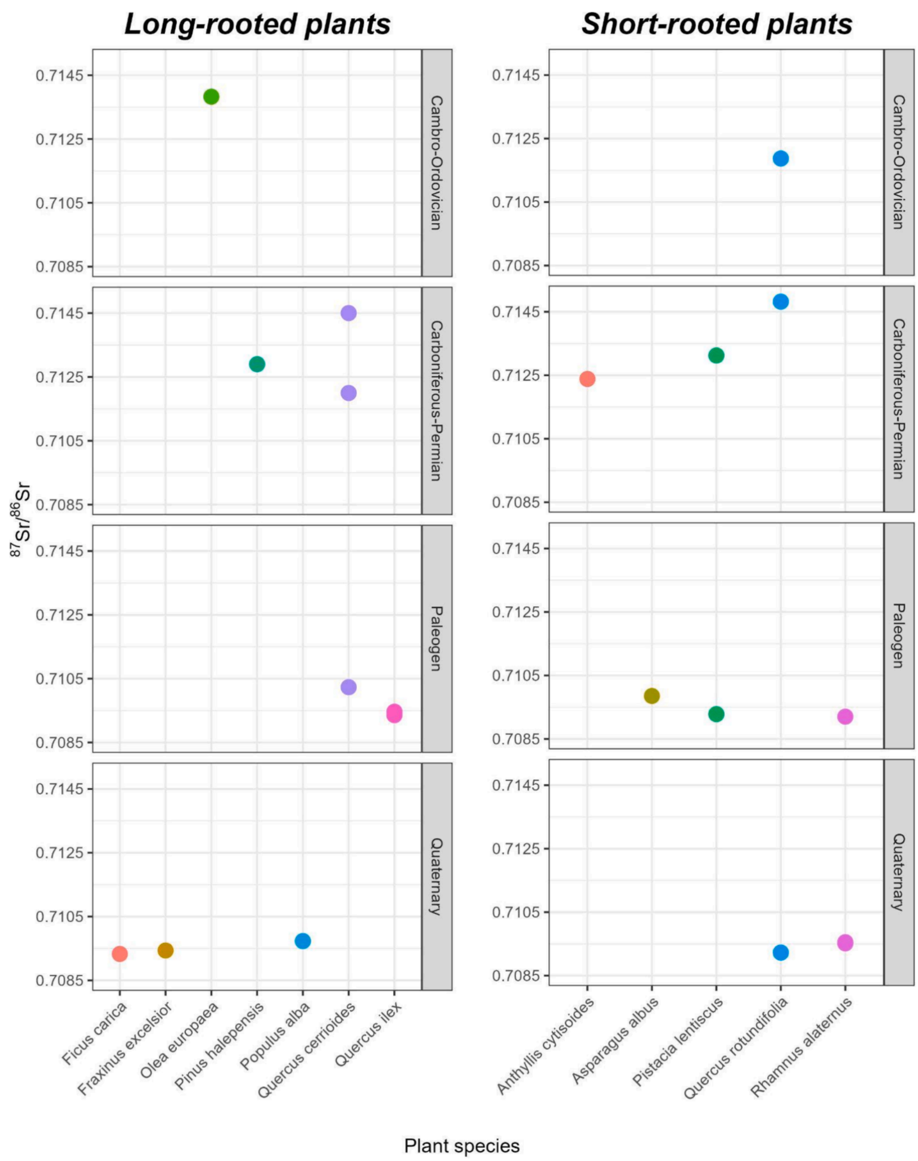

Fig. 6. Group of dot plots representing the values of the $^{87}Sr/^{86}Sr$ ratio from the different species of vegetation of both sites analysed in this work, divided by type of sample (long or short-rooted vegetation) and by geological period.

Since the distribution of the local strontium samples was normal (Shapiro-Wilk test: W = 0.95545, p-value = 0.4865), we applied the Student *t*-test to compare the local strontium means of Ullastret with the isotopic ratio of each of the human individuals at the site. We can see that only one human (ULL_HU3) would be local counting the *t*-test with the 95 % confidence interval: 0.7093—0.7096 (the dashed lines in Fig. 9) (see Table 8).

The distribution of the fauna is also normal (Shapiro-Wilk test: W = 0.9412, p-value = 0.5664) and when we compare the fauna values with those of locally bioavailable strontium, we observe that, except for ULL_CA1 (bovine), the rest of the animals are not consistent with the geologies of the surrounding areas of the Ullastret site (<2 km). (Fig. 9). In this sense, as mentioned earlier for Puig Castellar, the current vegetation and soil samples were collected in the areas closest to the site, and therefore, some of the locally bioavailable strontium values may not be represented, showing a certain bias in terms of the local isotopic baseline.

By adding the variable $\delta^{18}O$ and comparing it with the strontium values of fauna and humans (Fig. 10) the caprines (ULL_CP1, ULL_CP2 and ULL_CP3) have values close to each other, as well as humans (only two individuals), which also show values very close to the cattle. To determine whether there were identifiable patterns among species, we conducted Levene's test for homogeneity of variances. The results indicated no significant differences in oxygen values ($F(2, 6) = 0.6595$, $p = 0.5509$) or strontium values ($F(2, 6) = 0.2936$, $p = 0.7543$) between the species. A fact that, in our case, could be influenced by the small size of the sample analysed.

Most of the strontium fauna ratios, although outside the values provided by the baseline near the site, cluster close to the values obtained from the humans. However, there are exceptions, with some animals showing more radiogenic values, such as a pig (ULL_SU1) and a caprine (ULL_CP3), suggesting the possibility that these species were more mobile across the territory, although these animals then show similar oxygen values to the rest of the individuals analysed. The pigs, except for ULL_SU2 which shows a different trend from the rest, are located within a range of $\delta^{18}O$ very similar to the cattle. We also can see how ULL_SU1 moves away from this group due to the values of $^{87}Sr/^{86}Sr$ (ULL_HU1 and ULL_SU3 have not been included in the plot as they do not have $\delta^{18}O$ results). The discrepancies in oxygen values observed between individuals could be attributed to various factors (seasonality,

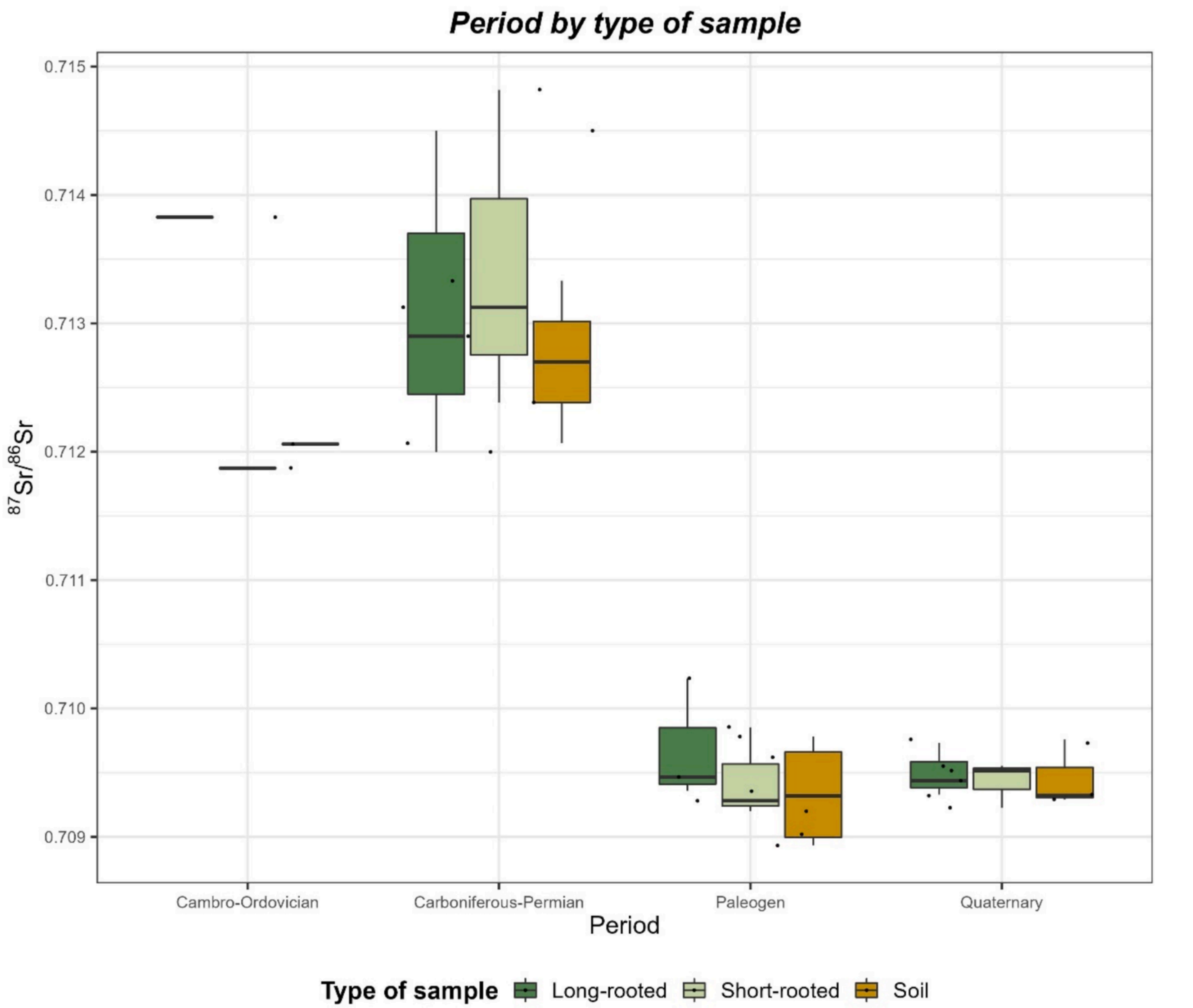

Fig. 7. Boxplot showing the values of the $^{87}Sr/^{86}Sr$ ratio from the local baseline samples analysed in this work, divided by geological period and type of sample. The geological periods are ordered from most ancient (left) to most recent (right).

Table 3
Sample information for human and faunal samples with $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ results from Puig Castellar.

Code	Site	Sample	Sex	Age	Tooth	Mineralisation age	$^{87}Sr/^{86}Sr$	$\delta^{18}O$ (‰ VPDB)
PC_HU1	Puig Castellar	Human	Undetermined	15	M_2	2.5y – 8.5y	0.7112	–
PC_HU2	Puig Castellar	Human	Male	18–25	P_1	2.5y – 6.5y	0.7094	–
PC_HU3	Puig Castellar	Human	Male	25–35	P_2	2.5y – 6.5y	0.7092	–
PC_HU4	Puig Castellar	Human	Male	18–25	M_3	8.5y – 15.5y	0.7088	–
PC_CA1	Puig Castellar	Cattle	–	Adult-senile	–	–	0.7123	−4.70
PC_CA2	Puig Castellar	Cattle	–	Adult-senile	–	–	0.7083	−6.15
PC_SU1	Puig Castellar	Suid	–	1y	–	–	0.7108	−5.11
PC_SU2	Puig Castellar	Suid	–	Adult	–	–	0.7132	−5.34
PC_SU3	Puig Castellar	Suid	–	Adult	–	–	0.7127	−4.89
PC_CP1	Puig Castellar	Caprine	–	2y	–	–	0.7104	−2.14
PC_CP2	Puig Castellar	Caprine	–	2y	–	–	0.7118	−0.55
PC_CF1	Puig Castellar	*Canis f.*	–	Senile	–	–	0.7107	−5.91

location, etc.), which we cannot fully assess without conducting a sequential analysis of the sample. However, if we examine the fauna values presented in the dendrograms attached in the supplementary material (S1, top of Fig. B.1 and the top left of Fig. B.2), we can observe that the mobility of the caprines appears to differ from that of the other fauna analysed. Interestingly, this occurs equally on both sites. These results do point us towards potential directions for future research about seasonal animal mobility in these regions.

Table 4
Local $^{87}Sr/^{86}Sr$ results from Puig Castellar. The type, geological unit, period, era, and rock type of the samples are provided.

Lab Code	Site	Sample type	GU	Era	Period	Rock Type	$^{87}Sr/^{86}Sr$
L-PC01	Puig Castellar	Plant	ÇOrP	Paleozoic	Cambro-Ordovician	Sedimentary rocks	0.7138
L-PC02	Puig Castellar	Plant	Ggd	Paleozoic	Cambro-Ordovician	Sedimentary rocks	0.7120
L-PC03	Puig Castellar	Plant	Gpg	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7121
L-PC04	Puig Castellar	Plant	Ggd	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7129
L-PC05	Puig Castellar	Plant	ÇOrP	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7133
L-PC07	Puig Castellar	Plant	Gpg	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7120
L-PC08	Puig Castellar	Plant	Ggd	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7145
L-PC09	Puig Castellar	Soil	Gpg	Paleozoic	Cambro-Ordovician	Sedimentary rocks	0.7119
L-PC10	Puig Castellar	Soil	Ggd	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7131
L-PC11	Puig Castellar	Soil	ÇOrP	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7148
L-PC12	Puig Castellar	Soil	Ggd	Paleozoic	Carboniferous-Permian	Intrusive rocks	0.7124

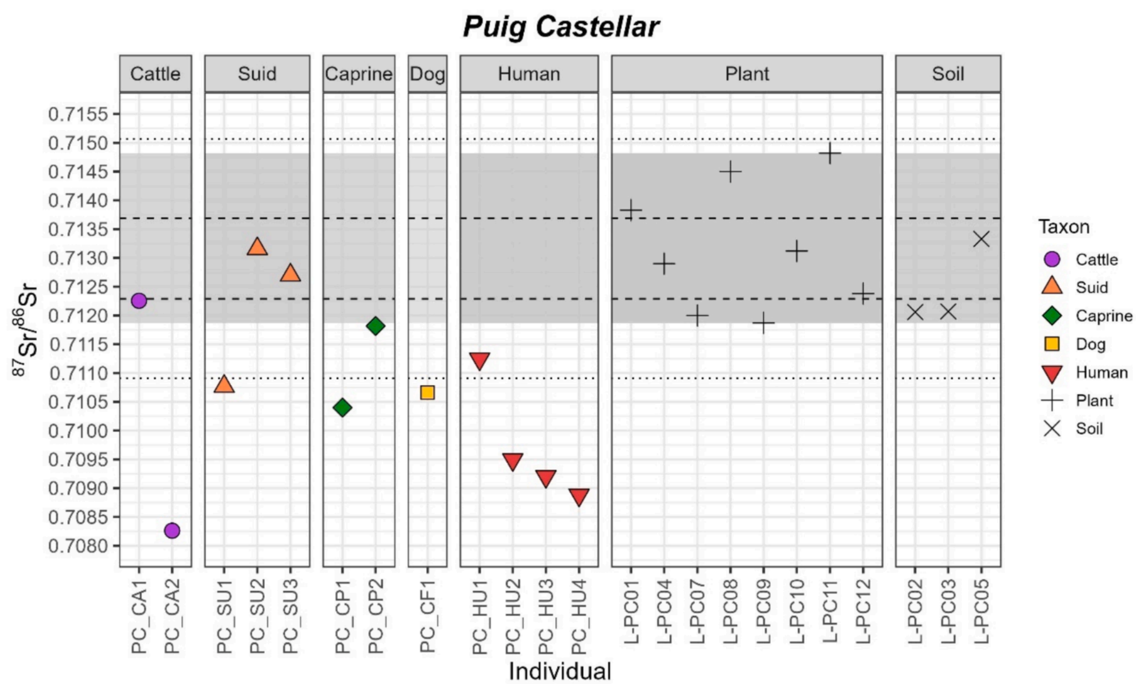

Fig. 8. Plot showing the individual values of $^{87}Sr/^{86}Sr$ for humans, fauna, and the local strontium from Puig Castellar. The dashed line marks the 95 % confidence interval (±2SE), the dotted line shows the variation of the baseline dataset (±2SD), and the grey area indicates the range between minimum strontium and maximum strontium.

Table 5
Student one sample *t*-test statistical values of the Puig Castellar human samples relative to the local strontium values.

Individual	Site	t value	df value	p value	Int. of conf.	Interpretation
PC_HU1	Puig Castellar	5.5721	10	0.0002367	95 %	Non local
PC_HU2	Puig Castellar	11.156	10	5.785e-07	95 %	Non local
PC_HU3	Puig Castellar	12.088	10	2.728e-07	95 %	Non local
PC_HU4	Puig Castellar	13.119	10	1.258e-07	95 %	Non local

4. Discussion

4.1. BASr in NE Iberia: Methodological Implications for archaeological mobility studies

Obtaining $^{87}Sr/^{86}Sr$ ratios is a key stage for establishing local strontium baseline ranges, which is essential in the investigation of mobility in past societies (Bentley et al., 2004; Böhlke and Horan, 2000; Bowen, 2010; Bowen et al., 2009; Ehleringer et al., 2010; Evans et al., 2010; Hobson et al., 2010; Hoppe and Koch, 2007; Price, 2023).

The establishment of these baseline ranges allows for the definition of territorial $^{87}Sr/^{86}Sr$ isoscapes and enables the identification of individual mobility across wide areas of landscape, helping to transcend the local/non-local dichotomy (Bataille et al., 2018; Bowen, 2010; Cavazzuti et al., 2019; Díaz-del-Río et al., 2022; Frank et al., 2021; Morell-Rovira et al., 2024; Scaffidi and Knudson, 2020).

To deal with this high geological variability, the sampling strategy focused on collecting vegetation (short- and long-rooted) and soil samples from as many different geological formations as possible within a range of < 2 km around the site, excluding anthropized or agriculturally affected areas (Cavazzuti et al., 2019; Snoeck et al., 2020). The application of QField and QGis software allowed the adjustment of the samplings when needed, as all the necessary information for the definition of a new sampling area was available in the field. The consistency

Table 6
Sample information for human and faunal samples with $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ results from Ullastret.

Code	Site	Sample	Sex	Age	Tooth	Mineralisation age	$^{87}Sr/^{86}Sr$	$\delta^{18}O$ (‰ VPDB)
ULL_HU1	Ullastret	Human	Male	20–25	M^3	8.5y – 15.5y	0.7092	–
ULL_HU2	Ullastret	Human	Male	20–30	M_3	8.5y – 15.5y	0.7107	−6.27
ULL_HU3	Ullastret	Human	Undetermined	17–25	M_1	4.5 m – 2.5y	0.7095	−6.11
ULL_CP1	Ullastret	Caprine	–	–	–	–	0.7092	−2.66
ULL_CP2	Ullastret	Cattle	–	–	–	–	0.7112	−4.41
ULL_CP3	Ullastret	Suid	–	–	–	–	0.7107	−5.26
ULL_CA1	Ullastret	Caprine	–	–	–	–	0.7098	−3.48
ULL_CA2	Ullastret	Cattle	–	–	–	–	0.7093	−5.12
ULL_CA3	Ullastret	Suid	–	–	–	–	0.7132	−4.73
ULL_SU1	Ullastret	Suid	–	–	–	–	0.7100	−7.97
ULL_SU2	Ullastret	Cattle	–	–	–	–	0.7108	−5.63
ULL_SU3	Ullastret	Suid	–	–	–	–	0.7087	–
ULL_SU4	Ullastret	Caprine	–	–	–	–	0.7125	−3.60

Table 7
Local $^{87}Sr/^{86}Sr$ results from Ullastret. The type, geological unit (GU), period, era and rock type of the samples are provided.

Code	Site	Sample type	GU	Era	Period	Rock type	$^{87}Sr/^{86}Sr$
L-ULL01	Ullastret	Soil	Peg	Cenozoic	Paleogene	Sedimentary rocks	0.7089
L-ULL02	Ullastret	Soil	PElg	Cenozoic	Paleogene	Sedimentary rocks	0.7096
L-ULL03	Ullastret	Soil	PElg	Cenozoic	Paleogene	Sedimentary rocks	0.7090
L-ULL04	Ullastret	Soil	T_Qpa	Cenozoic	Paleogene	Sedimentary rocks	0.7098
L-ULL05	Ullastret	Soil	Qpc	Cenozoic	Quaternary	Sedimentary deposits	0.7093
L-ULL06	Ullastret	Soil	Qac	Cenozoic	Quaternary	Sedimentary deposits	0.7093
L-ULL07	Ullastret	Soil	PEOa	Cenozoic	Quaternary	Sedimentary deposits	0.7098
L-ULL08	Ullastret	Plant	Peg	Cenozoic	Paleogene	Sedimentary rocks	0.7095
L-ULL09	Ullastret	Plant	PElg	Cenozoic	Paleogene	Sedimentary rocks	0.7094
L-ULL10	Ullastret	Plant	T_Qpa	Cenozoic	Quaternary	Sedimentary deposits	0.7094
L-ULL11	Ullastret	Plant	Qpc	Cenozoic	Quaternary	Sedimentary deposits	0.7097
L-ULL12	Ullastret	Plant	Qac	Cenozoic	Quaternary	Sedimentary deposits	0.7093
L-ULL13	Ullastret	Plant	PEOa	Cenozoic	Paleogene	Sedimentary rocks	0.7102
L-ULL14	Ullastret	Plant	Peg	Cenozoic	Paleogene	Sedimentary rocks	0.7092
L-ULL15	Ullastret	Plant	PElg	Cenozoic	Paleogene	Sedimentary rocks	0.7093
L-ULL16	Ullastret	Plant	T_Qpa	Cenozoic	Quaternary	Sedimentary deposits	0.7096
L-ULL17	Ullastret	Plant	Qpc	Cenozoic	Quaternary	Sedimentary deposits	0.7095
L-ULL18	Ullastret	Plant	Qac	Cenozoic	Quaternary	Sedimentary deposits	0.7092
L-ULL19	Ullastret	Plant	PEOa	Cenozoic	Paleogene	Sedimentary rocks	0.7099

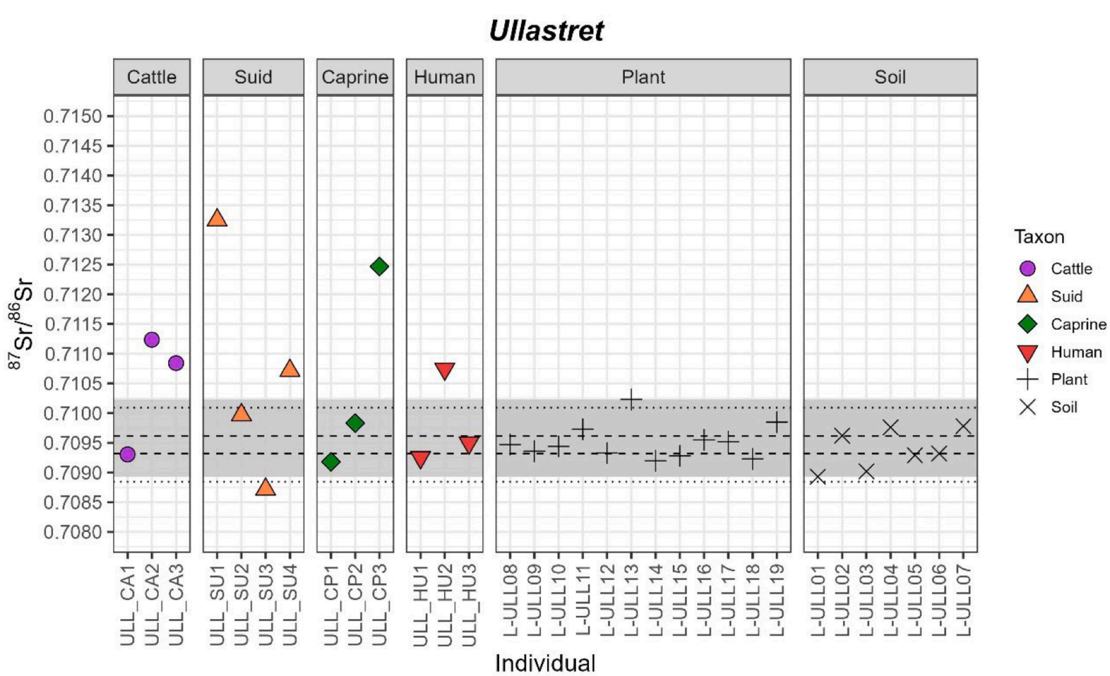

Fig. 9. Plot showing the individual values of $^{87}Sr/^{86}Sr$ for humans, fauna, and the local strontium from Ullastret. The dashed line marks the 95 % confidence interval, (±2SE), the dotted line shows the variation of the baseline dataset (±2SD), and the grey area indicates the range between minimum strontium and maximum strontium.

Table 8
Student's one sample *t*-test statistical values of the Ullastret human samples relative the local strontium values.

Individual	Site	t value	df value	p value	Int. of conf.	Interpretation
ULL_HU1	Ullastret	2.9853	18	0.007935	95 %	Non local
ULL_HU2	Ullastret	−17.778	18	7.279e-13	95 %	Non local
ULL_HU3	Ullastret	−0.43595	18	0.6681	95 %	Local

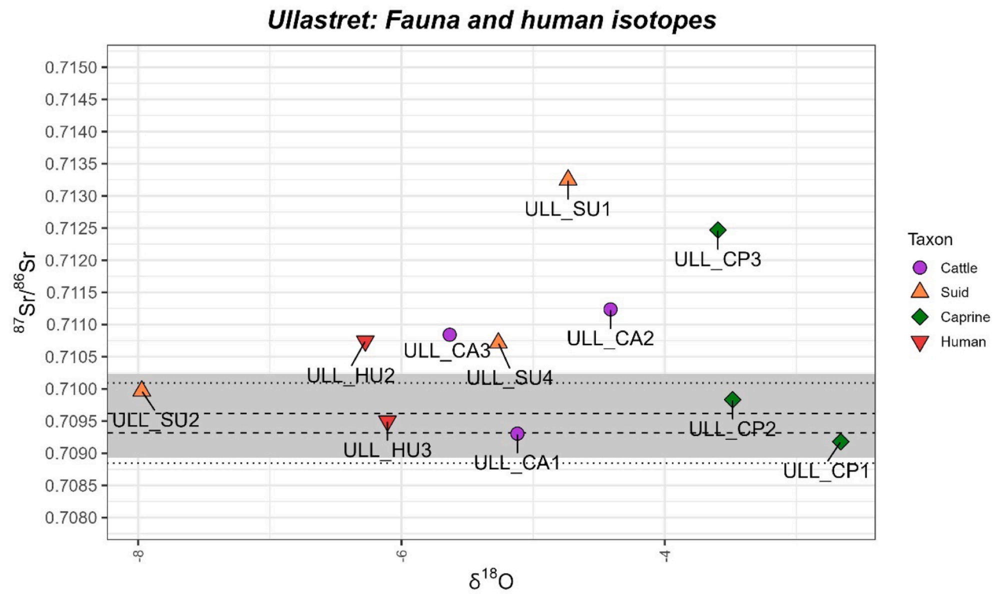

Fig. 10. Plot showing the values of $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ for humans and fauna of Ullastret. The dashed line marks the 95 % confidence interval, (±2SE), the dotted line shows the variation of the baseline dataset (±2SD), and the grey area the range between the minimum and maximum strontium value of the sediment and vegetation.

of the results in terms of underlying geology and the absence of outliers that could suggest foreign contamination (Fig. 5, Fig. 7) confirms the effectiveness of the proposed protocol as an effective way of collecting samples to generate the BASr baseline in the NE of the Peninsula.

The results from the sediment and vegetation samples have provided information that enables the establishment of several criteria for future studies, applicable to the geological landscape of the northeastern Iberian Peninsula for the creation of isoscapes. In this sense, since we have not found any notable difference between the type of sample and strontium isotope ratio variation, the samples collected at Puig Castellar

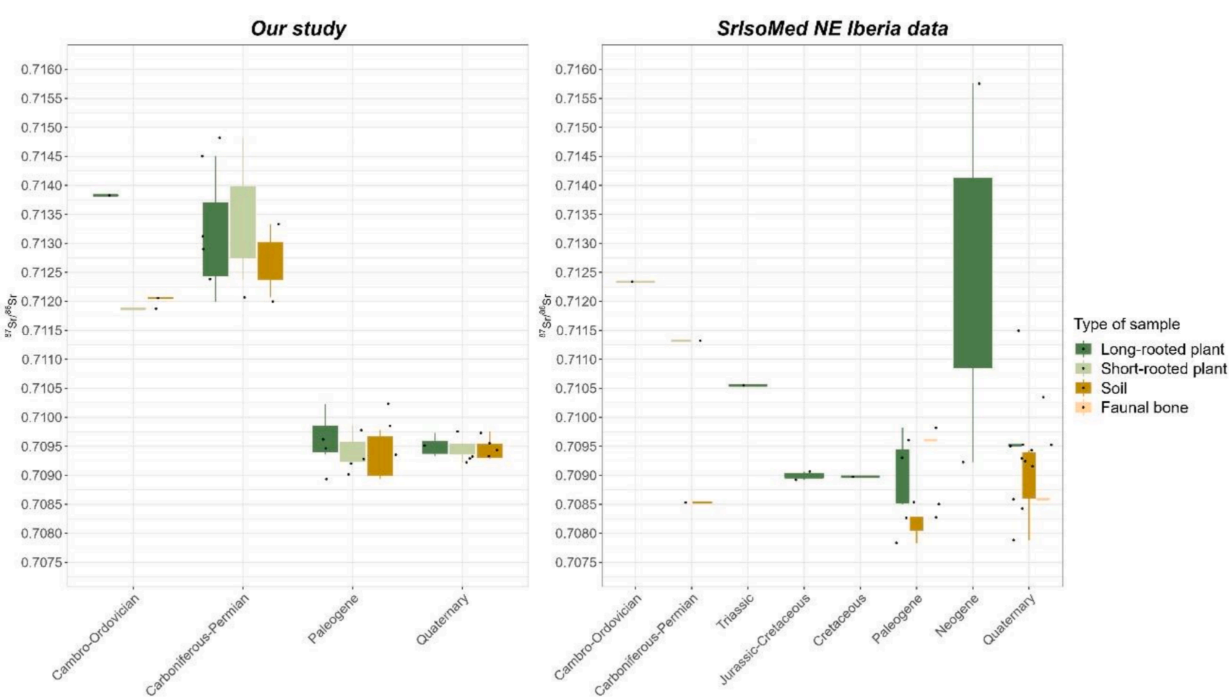

Fig. 11. Plot showing the $^{87}Sr/^{86}Sr$ values of the BASr samples collected in this study (left) and samples from other studies from the open database SrIsoMed (right).

and Ullastret show a clear trend: the formative period of the geological substrate is a greater determinant for the value of the $^{87}Sr/^{86}Sr$ ratio than the type of sample (soil, long-rooted or short-rooted plant). In order to test this hypothesis, we have compared our results with the data from the SrIsoMed database (Nikita et al., 2022) for NE Iberia (Fig. 11), most of our results are consistent, although there are some issues to highlight.

The Neogene long-rooted vegetation samples in SrIsoMed show a large variability. In this work we do not have data from this period to compare, but other unpublished studies we have conducted in the Penedes area (close to the SrIsoMed samples areas) show values coinciding with the lowest Neogene values in the database, suggesting that the higher values could be due to contamination. The soil samples show lower radiogenic values compared to ours and to other SrIsoMed studies, perhaps because they were collected for a Europe-wide study that collected samples from agricultural pastures and grazing lands. The only two bone samples are from sheep from archaeological contexts. Considering the porosity of the bones, it is easy to see that they reflect the BASr of their environment rather than their own due to contamination by diagenesis (Nelson et al., 1986). The Paleogene sheep bone is consistent with our values. The Quaternary bone does not, although it does coincide with Quaternary values that we analysed for another study (still unpublished) in a nearby area, where these bones were collected.

The differences in the values of the SrIsoMed samples with respect to our results are because they belong to different geological units. When the values coincide more closely, it is because they are geological units of similar lithological composition. It is important to note that the samples collected in our study come from highly anthropized areas and, even so, few outliers have been detected.

Based on the analyses presented in this work and the SrIsoMed data, ranges consistent with the $^{87}Sr/^{86}Sr$ ratio have been generated for each geological period (Table 9). To generate the SrIsoMed ranges, we removed the outlier from the Neogene long-rooted vegetation sample and from the soil samples.

As the variability of the SrIsoMed samples is greater than that of the samples analysed in this study, the proposed ranges for each geological period differ slightly between our analyses and those of SrIsoMed, although the observed trends remain consistent as the large difference in isotope ratio seems to be determined more by geology than by sample type.

4.2. Territorialisation and human mobility during Iberian period

The previously mentioned functional role of the sites is key for understanding the data. At Puig Castellar the only human individual that could have been local is PC_HU1 (Fig. 8 and Fig. 9) since this individual shows strontium values coincident with some faunal individuals, unlike the other humans (PC_HU2, PC_HU3 and PC_HU4). Our results of bioavailable strontium, together with those of the SrIsoMed database, show that values from areas with geological formations of more recent periods (such as the Paleogene or Quaternary) tend to have less radiogenic values than those from the Cambro-Ordovician or the Carboniferous-Permian (the Puig Castellar geology). In his sense, the majority of the fauna found in the site (caprine and suid) have provided values that are concordant to grazing in lower areas of the Catalan Coastal Mountain ranges, predominantly composed of geological formations from these more recent periods. Accordingly, as the values of PC_HU1 coincide with the values of these caprines and suids consumed in the site, we can argue that this human has isotopic values comparable to those of the nearby Puig Castellar geology. In contrast, the rest of the humans (PC_HU2, PC_HU3 and PC_HU4) would come from another area, with lower strontium ratio values, and probably geologically similar to the bovine PC_CA2.

In Ullastret, the values measured for two individuals (ULL_HU3 and ULL_HU1) are consistent with the baseline (Fig. 9). Amongst the fauna remains we observe a strong relationship between $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ data between bovine and suid management, strongly related to human mobility (S1, Fig. B.2.). Due the vast territory that Ullastret is believed to have controlled (Martín i Ortega and Plana i Mallart, 2001; Plana Mallart and Martín Ortega, 2012, 2003) it seems quite likely that all human individuals from Ullastret were moving around in the immediate vicinity of the settlement, related to the area of influence of the site. The coincidence of the human values with the faunal values suggests a similar mobility of both groups, especially taking into account what can be seen in Figs. 10 and S4 (S1, Fig. B.2.), where there is a coincidence of ULL_HU2 values with some archaeological faunal individuals (ULL_SU4, ULL_CA2, and ULL_CA3) all of which have values that do not differ from those of sediment and vegetation (Figs. 9 and 11). The area surrounding Ullastret is mainly formed by Quaternary, Paleogene, and Neogene formations, which could explain the lower values in the $^{87}Sr/^{86}Sr$ ratio of the baseline compared to Puig Castellar. However, there are some Cambro-Ordovician and Cretaceous geological formations less than 6 km from the site, which could explain why some individuals have very low values while others are close to the values expected for these geological units. The high $^{87}Sr/^{86}Sr$ values of pig and one cattle (ULL_SU1 and ULL_CP3) suggest a local mobility, namely from these geologically older areas. If we consider ULL_CP3 and ULL_SU1 as outliers, the bovines show slightly higher values than the other species which could indicate a wider catchment area (and even more in Puig Castellar) in relation to the $^{87}Sr/^{86}Sr$ results from both sites. These values are also consistent with previous studies that indicate that while during this period sheep and goat herds would have a very local seasonal mobility (Jiménez-Manchón et al., 2023; Messana et al., 2023; Nieto-Espinet et al., 2021, 2020; Valenzuela-Lamas et al., 2018, 2016), but other domestic species such as cattle or horses would be managed across exchange networks of greater territorial supply, which could be related to the life uses (such as animal traction) and role (prestige animal) that these species would have within Iberian communities (e.g: Nieto-Espinet et al., 2020; Valenzuela-Lamas et al., 2023). The absence of oxygen isotope data for all individuals, the small sample size analysed, and the non-sequential sampling of fauna prevent us from assessing key factors that are crucial for evaluating mobility in humans and animals during this period. In future studies, we will aim to consider factors such as seasonality, which may lead to variations in $\delta^{18}O$ values within the same territory.

These results align with the context of the Iberian period marked by a

Table 9

Isotopic ranges suggested for each period on the basis of the analyses presented in this paper (left) and from the SrIsoMed database (right).

Our study Period	n samples	Min value	Max value	Range value	SrIsoMed Period	n samples	Min value	Max value	Range value
Cambro-Ordovician	3	0.71187	0.71383	0.00195	Cambro-Ordovician	1	0.71234		
Carboniferous-Permian	9	0.71200	0.71482	0.00832	Carboniferous-Permian	2	0.70853	0.71132	0.00279
					Triassic	1	0.71055		
					Jurassic-Cretaceous	2	0.70892	0.70906	0.00014
					Cretaceous	1	0.70898		
Paleogene	10	0.70893	0.71023	0.00130	Paleogene	8	0.70783	0.70982	0.00199
					Neogene	1	0.70923		
Quaternary	9	0.70923	0.70976	0.00053	Quaternary	13	0.70788	0.71150	0.00361

pronounced social hierarchy, a significant expansion of agriculture, and increased commercial exchanges with other Mediterranean cultures. This scenario likely necessitated optimal animals for labour and light transportation. Simultaneously, the intensified processes of territorialization and the emerging pressure for land access would have compelled and the caprine herds to graze within the influence area of each site (e.g. Nieto-Espinet et al., 2020), a reality that would also impact the freedom of movement of human communities as suggested by the majority of local rages in Sr values.

4.3. Interpretations of severed heads: Local heroes or foreign enemies?

If we treat the humans of Puig Castellar and Ullastret as a whole (given that they represent a specific symbolic practice) it becomes challenging to determine whether the individuals analysed in this paper were external enemies, subjects of internal repression, or venerated ancestors.

The individuals from Puig Castellar were all found in an area of great public exhibition, such as the settlement's entrance gate (Fig. 2). We do not know if they were nailed to the wall or in some other area of the entrance, although the assumption that they were placed in the wall has led to interpreting these skulls as trophies of war. At Ullastret, the two individuals with strontium values that suggest they might have been locals are the two for which we know the location of their discovery: both in exposed areas within the settlement in zones 13 and 14 (Fig. 3). This information may support the hypothesis suggesting that the exposed remains would be important inhabitants of the settlement, possibly venerated or vindicated by society, perhaps associated with family groups or rival factions vying for power. In addition, the contexts in which these remains were found are interpreted as domestic units or dwellings (Agustí et al., 2016; Agustí and Díaz-Carvajal, 2015; Agustí and Martín, 2006; Oliver Foix, 1995). In contrast, the discovery of ULL_HU2 in a pit could align with the hypothesis that the served heads of "enemies" were brought as a trophy, and stored in boxes or pits, a practice documented among the Gauls of southern France (Ciesielski et al., 2011; Horn, 2003). However, historical records also suggest that the Gauls also placed skulls in public buildings (according to Strabo, cited Agustí et al., 2015; and Ciesielski et al., 2011) or in the houses of warriors (according to Diodorus Siculus, cited Agustí et al., 2015; and Ciesielski et al., 2011).

It should be noted, however, that all these chronicles that mention the severed (or nailed) heads of the enemies as war trophies are based on the writings of the Greek Posidonius of Apameia, who travelled through southern Gaul at the end of the 2nd century BCE, and that the texts of Diodorus and Strabo were written much later (Agustí et al., 2015). Moreover, according to the ancient chronicles, it is not certain that the criteria followed in Ullastret or Puig Castellar for this practice were the same as those observed in southern Gaul. Not much is specified about the Iberians of northeastern Iberia, only small fragments mentioning that the Iberian mercenaries carried impaled enemy heads on their spears (Ciesielski et al., 2011), and that the Lusitanians practised sacrifices of severed limbs of enemies, such as hands or heads, although it remains unclear whether these cases refer to Iberian populations or to "barbarians", due to translation ambiguities in the original texts (Agustí et al., 2015).

Most authors have tended to propose that most of the individuals come from elsewhere (Agustí and Martín, 2006; Ciesielski et al., 2011; De la Pinta Rodríguez and Río-Miranda Alcón, 1981), defending the hypothesis that the skulls belonged to enemies defeated in combat and were exhibited as war trophies. In contrast, the results from the present work suggest that the human mobility is much more complex than it seems, and these skulls could came from local individuals. In fact, the existence of mobility in this period and region is well documented, as shown by the aDNA results by Fischer et al. (2022), In this work they show some interregional mobility and genetic affinities between Gauls from southern France and groups from the Iberian Peninsula. In addition, they suggest that one individual from Ullastret analysed by Olalde et al. (2019) would have a genetic heritage compatible with the British isles (Fischer et al., 2022).

Therefore, it might be that the practice of severed heads obeys several criteria, such as the sociocultural differences between sites (Ullastret and Puig Castellar applying this practice in different ways) or, depending on the location of the remains, different motivations (exposed on walls, placed in pits, stored inside specific buildings, etc.). Neither do the anthropological analyses provide any further insight into this, since there is evidence of weapon injuries in some of the skulls from both sites, although we do not observe a pattern associating violent deaths (the lesions are perimortem) with any particular site or type of exposition (De Prado and Rovira Hortalà, 2015; Subirà and Rovira Hortalà, 2019). In this sense, the different proposals by several authors suggest that, in some cases, we can speak of enemies and in others of venerated ancestors (Agustí et al., 2016; Agustí and Díaz-Carvajal, 2015; Agustí and Martín, 2006; Oliver Foix, 1995). These are still empirical hypotheses that we cannot exclude at this point.

5. Conclusions

The individuals analysed in this study, in the majority males, represent fortuitous and exceptional finds within Iberian society. These human remains, arising from a specific ritual practice involving decapitation, do not appear to have been selected randomly. These severed heads reveal a homogeneous trend in terms of sex, as all are male; however, the mobility and depositional patterns suggest greater diversity, implying social or cultural differences among individuals from these two Iron Age communities. At Puig Castellar, severed heads in public areas could demonstrate power, venerate important community members, or intimidate enemies. At Ullastret, the location of the heads in exposed areas suggests they were important inhabitants, venerated by local society. Recent anthropological studies have identified female individuals similar to those examined in this research. Further analysis of these remains could yield valuable insights into these societies. This information is crucial for understanding the symbolic practices of Iberian societies in northeastern Iberia.

The isotopic analysis of the severed heads from Puig Castellar and Ullastret provides new details into human mobility during the Iberian period (6th-1st centuries BCE). The results reveal a variety of interactions between individuals with different mobility and can highlight different social and economic dynamics.

At Puig Castellar, strontium isotope data suggest that only one human individual would have a mobility consistent with the geology near the settlement. This idea gains support due to the fact that these values are coincident with those of the livestock interpreted as local from previous studies. The other three individuals show strontium values pointing to a different mobility, compatible with regions with more recent geological formations. This suggests a mix of different mobilities subjected to the rituals of decapitation and exhibition. Conversely, at Ullastret, the isotopic data align with local baselines, indicating that the analysed individuals were moving in areas surrounding the settlement. The similarity between human and livestock isotopic values supports this idea, and the broader variability in Ullastret's isotopic values suggests a larger resource catchment area compared to Puig Castellar. These differences could be related to the different functions of the two sites, with Ullastret being a major Iberian city and administrative centre controlling a more extensive territory, whereas Puig Castellar is identified as a second-order site, more focused on local territorial control.

Our results reveal, for the first time, direct evidence of human mobility patterns in the Iron Age, that offer new perspectives for the contexts of territorialisation in NE Iberia. The coexistence of different mobility patterns at both sites suggests variations in the size of resource catchment areas and management strategies, coherent with the typology of two analysed sites. This reflecting a dynamic and complex society with significant local and external interactions. At the same time, they suggest that the selection of individuals for the severed head ritual was more complex than initially believed. This study underscores the importance of integrating bioarchaeological and isotopic data to enhance our understanding of social structures and human interactions in ancient societies.

Funding sources

This work was supported by the Palarq Foundation (2019) and by the Agència Catalana del Patrimoni Cultural (2014) and with the support of the research doctoral grant FI-DGR 2019 of the Secretaria d'Universitats i Recerca of the Generalitat de Catalunya and the European Social Fund.

DLO was supported by the ANR AERC grant (project number 0005).

CRediT authorship contribution statement

Rubén de la Fuente-Seoane: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Methodology, Writing – original draft, Writing – review & editing. **Diego López-Onaindia:** Writing – review & editing, Writing – original draft, Conceptualization. **Ferran Codina Falgas:** Writing – review & editing, Resources. **Gabriel De Prado:** Writing – review & editing, Resources. **Conxita Ferrer Álvarez:** Writing – review & editing, Resources. **M. Carme Rovira Hortalà:** Writing – review & editing, Resources. **Marta Díaz-Zorita Bonilla:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Ariadna Nieto-Espinet:** Writing – review & editing, Supervision, Conceptualization. **M. Eulàlia Subirà:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Acknowledgments

We would like to thank the training, and the technical and human support provided by Dr. Javier Rodrguez Aller, Dr. Luis Angel Ortega and the SGIker of UPV/EHU and European funding (ERDF and ESF). This study has also received scientific environmental support from the French government in the framework of the University of Bordeaux's IdEx "Investments for the Future" program/GPR Human Past, and of the teams COMOS and EVODIBIO from PACEA-UMR5199. Finally, we want to thank the reviewers for their insightful and valuable feedback, which has greatly enhanced the quality and clarity of our manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105035.

Data availability

All research data and code are attached as supplementary materials (S2 and S3) and the link to the repository where the supplementary material S3 is stored is also attached.

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