



TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC): A MULTI-ISOTOPE RESEARCH

Chiara Messana

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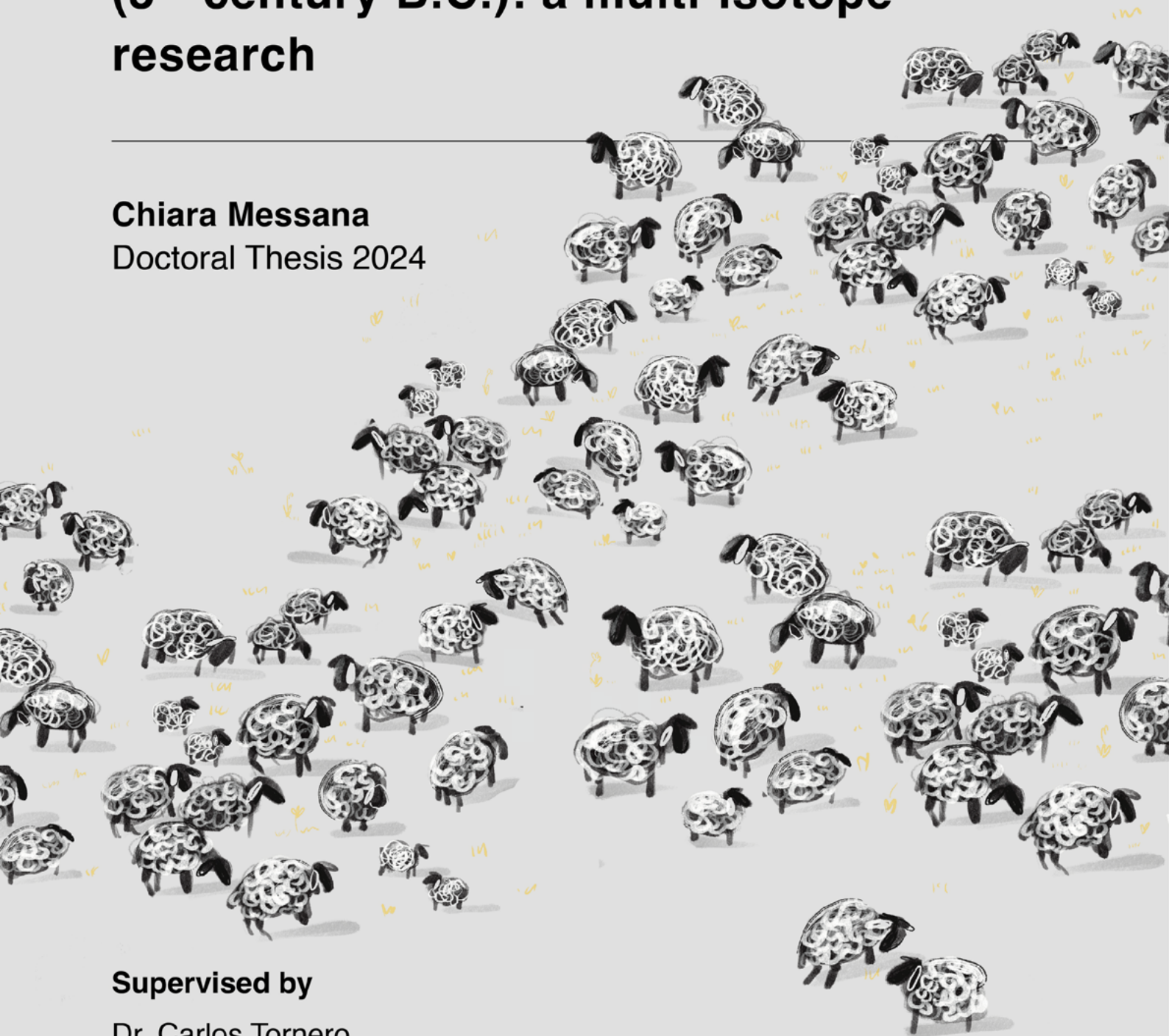


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ROVIRA I VIRGILI



Tales of sheep in the north-eastern Iberian Peninsula during the Iron Age (3rd century B.C.): a multi-isotope research

Chiara Messana
Doctoral Thesis 2024



Supervised by

Dr. Carlos Tornero
Dr. Lidia Colominas

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UNIVERSITAT ROVIRA I VIRGILI

Tarragona

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FAIG CONSTAR que aquest treball, titulat "Tales of sheep in the north-eastern Iberian Peninsula during the Iron Age (3rd century BC): a multi-isotope research", que presenta Chiara Messana per a l'obtenció del títol de Doctor, ha estat realitzat sota la meua direcció al Departament d'Història i Història de l'Art d'aquesta universitat.

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I STATE that the present study, entitled "Tales of sheep in the north-eastern Iberian Peninsula during the Iron Age (3rd century BC): a multi-isotope research", presented by Chiara Messana for the award of the degree of Doctor, has been carried out under my supervision at the Department of History and History of Art of this university.

Tarragona, 26/02/2024

El/s director/s de la tesi doctoral

El/los director/es de la tesis doctoral

Doctoral Thesis Supervisor/s

Carlos Tornero Dacasa

Lidia Colominas Barberà

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*A mia madre, roccia delicata,
a mio padre, costretto ad allontanarsi un attimo.*

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“E la regola secondo me è: quando sei a un bivio e trovi una strada che va in su e una che va in giù, piglia quella che va in su. E più facile andare in discesa, ma alla fine ti trovi in un buco. A salire c'è speranza.” Tiziano Terzani, “La fine è il mio inizio.”

“And, in my opinion, the rule is: when you are at a crossroads and you find a road going up and one going down, take the one that goes up. Going downhill is easier, but eventually, you find yourself in a hole. There is hope going up.” Tiziano Terzani, “The end is my beginning.”

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Abstract

During the Iron Age, communities in the north-eastern Iberian Peninsula relied on cereal cultivation and livestock husbandry for subsistence. Regarding husbandry, no data on in-life livestock management and, specifically, sheep is currently available. The latter was the predominant species due to its suitability to the Mediterranean climate, orography and environment and the wide variety of products it provided.

To address this lacuna, this doctoral research has employed a biogeochemical approach (stable isotopes) to gain novel and in-depth insights into the livestock management strategies adopted in four relevant Catalan sites dating back to the 3rd century BC: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira. Multi-isotopic analyses have made it possible to investigate, with direct evidence and a seasonal temporal resolution, the three core elements of any livestock system: reproduction patterns, mobility strategies, and feeding habits of sheep.

Firstly, the sequential analyses of oxygen isotope values ($\delta^{18}\text{O}$) of the sheep's second and third molars revealed diversified reproduction patterns, with anthropogenic manipulation of both the season and the duration of lambing.

Secondly, the combination of sequential analyses of $\delta^{18}\text{O}$ and carbon ($\delta^{13}\text{C}$) values with strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) in the sheep's dental enamel uncovered evidence of movement across different altitudinal and geological areas. Nevertheless, livestock mobility was not widely practised. Furthermore, the study recorded the first evidence of descending herds' mobility from the Pyrenees to the lowlands, suggesting a more integrated and connected Ibero-Pyrenean world than previously recognised.

Thirdly, bulk $\delta^{13}\text{C}$ and nitrogen ($\delta^{15}\text{N}$) isotope analyses on bone collagen combined with sequential analyses of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope values on teeth shed light on sheep dietary habits. The results indicate minimal variations in diet, with a predominant consumption of C_3 plants and seasonal variations in feeding habits. The other main

domestic species (goats, cattle, and pigs) were subject to individualised feeding strategies.

Overall, this multi-isotope research provides an in-depth comprehension of the sheep husbandry practices adopted by Iron Age Iberian communities. The results outline a self-sufficient husbandry within each of the four settlements. However, livestock husbandry was complex on a local scale. Indeed, every community selected the strategies to adopt depending on settlement requirements, considering the products to exploit, environmental conditions, economic needs, and political decisions.

Resum

Durant l'Edat del Ferro, les comunitats ibèriques del nord-est peninsular basaven la seva subsistència en l'agricultura cerealística i la ramaderia. Respecte a aquesta última, no existeixen dades sobre la gestió en vida del bestiar, especialment de les ovelles, tot i que aquesta espècie era la predominant a causa de la seva adaptabilitat al clima, orografia i ambient mediterrani, així com per l'àmplia gamma de productes que podia proporcionar.

Amb l'objectiu d'omplir aquest buit d'informació, la present recerca doctoral ha emprat un enfocament biogeoquímic (isòtops estables) per obtenir una visió nova i exhaustiva de les estratègies de gestió del bestiar adoptades en quatre jaciments rellevants de la Catalunya actual, datats al segle III aC: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius i Turó de la Rovira. L'ús d'anàlisis multi-isotòpiques ha permès investigar, amb evidències directes i amb una resolució a escala estacional, els tres aspectes fonamentals d'un sistema ramader oví: els patrons de reproducció, les estratègies de mobilitat i els hàbits alimentaris.

En primer lloc, les anàlisis seqüencials dels valors isotòpics de l'oxigen ($\delta^{18}\text{O}$) en els segons i els tercers molars d'ovelles han revelat diversos patrons de reproducció, amb manipulació antròpica tant de l'estació com de la durada del període de naixement.

En segon lloc, la combinació d'anàlisis seqüencials dels valors de $\delta^{18}\text{O}$ i carboni ($\delta^{13}\text{C}$) amb les ràtios isotòpiques d'estronci ($^{87}\text{Sr}/^{86}\text{Sr}$) en l'esmalt dental de les ovelles ha revelat moviments de ramats al llarg de diferents àrees altitudinals i geològiques. Malgrat tot, la mobilitat a gran escala dels ramats no seria una pràctica generalitzada. Tot i això, s'han registrat els primers testimonis de mobilitat descendent dels ramats des dels Pirineus cap a les terres baixes, la qual cosa suggereix la imatge d'un món ibero-pirinenc més integrat i connectat del que es reconeixia fins ara.

En tercer lloc, les anàlisis isotòpics 'bulk' de $\delta^{13}\text{C}$ i nitrogen ($\delta^{15}\text{N}$) en el col·lagen ossi, en combinació amb les anàlisis seqüencials dels valors isotòpics de $\delta^{13}\text{C}$ i $\delta^{18}\text{O}$ en les dents, han proporcionat informació sobre els hàbits alimentaris de les ove-

lles. Els resultats indiquen variacions mínimes en la dieta, amb un predomini del consum de plantes C_3 i hàbits alimentaris subjectes a canvis estacionals. Les altres espècies domèstiques principals estaven sotmeses a estratègies alimentàries individualitzades.

Per tant, el present estudi multi-isotòpic permet conèixer amb més profunditat les pràctiques ramaderes ovines adoptades per les comunitats ibèriques de l'Edat del Ferro. Els resultats mostren una ramaderia complexa a escala local i autosuficient en cadascun dels quatre assentaments. De fet, cada comunitat triava les estratègies a adoptar en funció de les seves necessitats específiques, considerant els productes a explotar, però també les condicions ambientals, les necessitats econòmiques i les decisions polítiques.

Resumen

Durante la Edad del Hierro, las comunidades íberas del noreste peninsular basaban su subsistencia en la agricultura cerealística y la ganadería. Respecto a esta última, no existen datos sobre la gestión en vida del ganado, sobre todo de las ovejas, a pesar de que esta especie era la predominante debido a su adaptabilidad al clima, orografía y ambiente mediterráneo, así como por la amplia gama de productos que podía proporcionar.

Con el objetivo de colmar este vacío de información, la presente investigación doctoral ha empleado un enfoque biogeoquímico (isótopos estables) para obtener una visión novedosa y exhaustiva de las estrategias de gestión del ganado adoptadas en cuatro yacimientos relevantes de la Cataluña actual, datados en el siglo III a.C.: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius y Turó de la Rovira. El empleo de análisis multi-isotópicos ha permitido investigar, con evidencias directas y con una resolución a escala estacional, los tres aspectos fundamentales de un sistema ganadero: los patrones de reproducción, las estrategias de movilidad y los hábitos alimentarios de las ovejas.

En primer lugar, los análisis secuenciales de los valores isotópicos del oxígeno ($\delta^{18}\text{O}$) en los segundos y terceros molares de ovejas han revelado diversos patrones de reproducción, con manipulación antrópica tanto de la estación como de la duración del periodo de nacimiento.

En segundo lugar, la combinación de análisis secuenciales de los valores de $\delta^{18}\text{O}$ y carbono ($\delta^{13}\text{C}$) con las ratios isotópicas de estroncio ($^{87}\text{Sr}/^{86}\text{Sr}$) en el esmalte dental de las ovejas ha revelado movimientos a lo largo de diferentes áreas altitudinales y geológicas. A pesar de ello, la movilidad de los rebaños no estaba generalizada. Sin embargo, se han registrado los primeros testimonios de movilidad descendente de los rebaños desde los Pirineos hacia las tierras bajas, lo que sugiere la imagen de un mundo íbero-pirenaico más integrado y conectado de lo que se reconocía hasta ahora.

En tercer lugar, los análisis isotópicos 'bulk' de $\delta^{13}\text{C}$ y nitrógeno ($\delta^{15}\text{N}$) en el colágeno óseo, en combinación con los análisis secuenciales de los valores isotópicos de $\delta^{13}\text{C}$ y $\delta^{18}\text{O}$ en los dientes, han proporcionado información sobre los hábitos alimentarios de las ovejas. Los resultados indican variaciones mínimas en la dieta, con predominio del consumo de plantas C_3 , y hábitos alimentarios sujetos a cambios estacionales. Las otras especies domésticas principales estaban sometidas a estrategias alimentarias individualizadas.

En general, el presente estudio multi-isotópico permite conocer con mayor profundidad las prácticas ganaderas ovinas adoptadas por las comunidades íberas de la Edad del Hierro. Los resultados muestran una ganadería compleja a escala local y autosuficiente en cada uno de los cuatro asentamientos. En efecto, cada comunidad elegía las estrategias a adoptar en función de las necesidades específicas del asentamiento, considerando los productos a explotar, pero también las condiciones ambientales, las necesidades económicas y las decisiones políticas.

Riassunto

Durante l'età del Ferro, le comunità iberiche del nord-est basavano la propria sussistenza sull'agricoltura cerealicola e sull'allevamento. Per quest'ultimo non sono disponibili dati sulla gestione in vita del bestiame, in particolare delle pecore. Questa specie era predominante grazie alla sua adattabilità al clima, all'orografia e all'ambiente mediterraneo, nonché alla vasta gamma di prodotti che garantisce.

Per colmare questa lacuna, la presente ricerca di dottorato ha impiegato un approccio biogeochimico (isotopi stabili) per ottenere una visione inedita e approfondita delle strategie di gestione del bestiame adottate in quattro siti rilevanti dell'attuale Catalogna, datati al III secolo a.C.: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, e Turó de la Rovira. L'impiego delle analisi multi-isotopiche ha consentito di indagare, con evidenza diretta e con una risoluzione a scala stagionale, i tre aspetti fondamentali di ogni sistema d'allevamento: i modelli di riproduzione, le strategie di mobilità e le abitudini alimentari delle pecore.

In primo luogo, le analisi sequenziali dei valori isotopici dell'ossigeno ($\delta^{18}\text{O}$) nei secondi e terzi molari di pecore hanno rivelato modelli di riproduzione diversificati, con manipolazione antropica sia della stagione di nascita sia della durata del periodo di agnellatura.

In secondo luogo, la combinazione delle analisi sequenziali dei valori di $\delta^{18}\text{O}$ e carbonio ($\delta^{13}\text{C}$) con i rapporti isotopici dello stronzio ($^{87}\text{Sr}/^{86}\text{Sr}$) nello smalto dentale delle pecore ha evidenziato movimenti delle greggi lungo differenti aree altitudinali e geologiche. Nonostante questo, la mobilità del bestiame non era ampiamente praticata. Inoltre, è stata registrata la prima evidenza di mobilità discendente del gregge dai Pirenei verso il fondovalle, suggerendo un'immagine di un mondo Ibero-Pirenaico più integrato e connesso rispetto a quanto riconosciuto in precedenza.

In terzo luogo, le analisi 'bulk' degli isotopi del $\delta^{13}\text{C}$ e dell'azoto ($\delta^{15}\text{N}$) sul collagene osseo, in combinazione con le analisi sequenziali dei valori isotopici di $\delta^{13}\text{C}$ e $\delta^{18}\text{O}$

sui denti, hanno fornito informazioni sulle abitudini alimentari delle pecore. I risultati indicano variazioni minime nella dieta, con un consumo predominante di piante C_3 , e abitudini alimentari soggette a cambiamenti stagionali. Le altre principali specie domestiche erano sottoposte a strategie alimentari individualizzate.

In generale, questo studio multi-isotopico fornisce una comprensione approfondita delle pratiche di allevamento degli ovini adottate dalle comunità iberiche dell'età del Ferro. I risultati delineano un allevamento del bestiame autosufficiente all'interno di ognuno dei quattro insediamenti. Nonostante questo, l'allevamento era complesso a scala locale. Infatti, ogni comunità sceglieva le strategie da adottare in base alle esigenze specifiche dell'insediamento, considerando i prodotti da sfruttare, le condizioni ambientali, le necessità economiche e le decisioni politiche.

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Thesis presentation and structure

1. Thesis presentation

The present doctoral thesis stems from the urge to take a step forward in the comprehension of livestock husbandry in the north-eastern Iberian Peninsula during the Iron Age. In this chronotopic context, extensive data collection exists on agricultural practices, traditionally considered the main economic activity, and husbandry. The latter has been investigated through traditional zooarchaeological analyses, which have allowed the gathering of information on the composition and exploitation of livestock and their general characteristics. Through these studies, it has been possible to recognize the sheep as the dominant species in Iberian husbandry during the Iron Age. However, the knowledge acquired, although abundant, has not succeeded in outlining the in-life management of livestock and, specifically, of sheep by Iberian communities.

The author of this thesis has a background in zooarchaeological studies, particularly in earlier chronologies. Her master's thesis focused on the zooarchaeological and

taphonomic analysis of the faunal assemblage from Casa Gazza, a site in north-eastern Italy dated to the Early Neolithic period. Her subsequent traineeship (or more accurately, 'traineeship') at IPHES, under the supervision of Dr. Josep Maria Vergès, Dr. Patricia Martín, and Dr. Carlos Tornero, was developed on this chronological period, conducting zooarchaeological and biogeochemical analyses (stable isotopes) on faunal remains from the Ancient Neolithic phase of the Font Major cave site (north-east of the Iberian Peninsula).

Isotope analyses are widely integrated in zooarchaeology to study husbandry strategies. They yield novel and in-depth information on livestock management due to their resolution on a seasonal temporal scale and the direct evidence provided. In the north-east of the Iberian Peninsula, this research line has mainly focused on Neolithic chronologies, offering new insights into early husbandry practices.

This biogeochemical approach in protohistoric chronologies is still underused. The encounter of the

author of this doctoral thesis with the directors Dr. Carlos Tornero and Dr. Lúdia Colominas resulted in the development of this PhD project. Indeed, the conception of this doctoral dissertation stems precisely from the desire to exploit the enormous potential offered by multi-isotope analyses to finally address this lacuna in the study of livestock husbandry practices of Iron Age Iberian communities. Thus, the following pages narrate the tales of sheep in the north-eastern Iberian Peninsula during the Iron Age (3rd century B.C.) through a multi-isotope approach.

2. Thesis structure

This doctoral thesis, structured as a compendium of four publications, is divided into six main chapters.

The first chapter, *Introduction*, presents the topic of the thesis. It sets the scene for this research, providing the historical context and focusing on the available information on livestock exploitation during the Iron Age in the north-eastern Iberian Peninsula (present-day Catalonia). Furthermore, this session provides an overview of stable isotope analysis principles to investigate herding strategies.

The second chapter, *Research objectives*, outlines the main aim of this doctoral dissertation, which was addressed through three research objectives. Furthermore, it elucidates the rationales for selecting the four examined archaeological sites.

The third chapter, *Materials and methods*, introduces the four sites studied in this doctoral thesis and their selected faunal remains (teeth and bones). Further, the biogeochemical methods employed to analyse the archaeological remains

are outlined. Finally, the statistical analyses performed on the data obtained are listed.

The fourth chapter, *Results*, presents the results of this research project in the form of four articles, three of which have been published or accepted, and one is currently under review. Each of them is reported here in its original format. The results are organised according to the research objectives of this doctoral thesis. The bibliographical references of these publications are provided below:

1a. Messana, C., Tornero, C., Colominas, L., Pons, E. (accepted). An insight of sheep's seasonal reproductive patterns on the northeastern Iberian Peninsula before the Roman influence: The Case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain). *BAR publishing*, Oxford.

1b. Messana, C., Tornero, C., Colominas, L. (2023). Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula (3rd c. BC). *Archaeological and Anthropological Sciences*, 15(5), 56. <https://doi.org/10.1007/s12520-023-01752-1>

2. Messana, C., Tornero, C., Madgwick, R., Lamb, A., Evans, J., Colominas, L. (2023). Between valleys, plateaus, and mountains: unveiling livestock altitudinal mobility in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope approach. *Frontiers in Environmental Archaeology*, 2. <https://doi.org/10.3389/fearc.2023.1245725>

3. Messana, C., Tornero, C., Colominas, L. (under review). Beyond the herd: investigating livestock feeding strategies in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope analysis. *Archaeological and Anthropological Sciences*.

The fifth chapter, *Discussion*, summarises the main contributions of this doctoral thesis, following each of the three research objectives. Additionally, it also addresses the methodological inputs provided by our study. This doctoral thesis is structured as a compendium of articles, each of which includes a discussion. This section, therefore, recapitulates the discussions presented in the previous chapter (4. Results), focusing on the most significant issues raised.

The sixth chapter, *Conclusion and future perspectives*, outlines the main contributions of this doctoral dissertation. Further, it reports on the collateral themes that have emerged from this research, worthy of further, parallel investigation.

To conclude, the list of bibliographical references is followed by the appendix, which provides: the list of tables and figures, other publications, the list of conferences, and the annex containing the supplementary material from each of the four articles.

UNIVERSITAT ROVIRA I VIRGILI

TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC) : A MULTI-ISOTOPE RESEARCH

Chiara Messina



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Introduction

1.1 Livestock exploitation during the Iron Age in the north-eastern Iberian Peninsula

During the Iron Age, Iberian communities in the north-eastern Peninsula were organised into proto-state structures, strongly hierarchical and arranged into several centralised political entities (Gracia, 2005; Almagro-Gorbea, 2014; Sanmartí, 2014, 2021). The settlement pattern was organised through a wide network of interconnected open-air centres, each serving specific functions, i.e. fortified centres, rural establishments, small villages, and silo fields (Gracia, 2005; Sanmartí, 2014, 2021). All these settlements were structured around central nuclei, the so-called first-order cities, which primarily controlled and centralised agricultural production (Asensio *et al.*, 1998; Bouso *et al.*, 2000; Sanmartí, 2004, 2014; Sanmartí *et al.*, 2019). The subsistence strategies of these communities revolved around peasant economies, with cereal agriculture as the main source of subsistence. Agricultural practices were devoted to self-sufficiency, with

cereal surplus being the main exchange product (Asensio *et al.*, 2003a; Asensio, 2013; Prats *et al.*, 2020).

In the north-eastern Iberian Peninsula, wheat (*Triticum aestivum/durum*) and barley (*Hordeum vulgare*) were the dominant crops, supplemented by millet (*Panicum miliaceum*) and leguminous plants (*Lens culinaris*, *Pisum sativum*, *Vicia faba*) as secondary crops (Alonso, 2000; Riera *et al.*, 2020). A high level of complexity in crop management has been attested, potentially involving rotation cycles in cultivation practices (Alonso, 2000; Riera *et al.*, 2020).

Alongside crop cultivation, herding practices were also a fundamental activities for ensuring the growth and sustainability of these Iron Age communities. Over two decades of zooarchaeological research have enabled the characterisation of livestock husbandry practices in the north-eastern Iberian Peninsula during this period. This involved diversification in the exploitation of various domestic *taxa* (sheep, goats, cattle, pigs, dogs,

horses, rabbits, and chicken), allowing for a reduction in dependence on a single species and the acquisition of diversified animal resources (Franquesa *et al.*, 2000; Colominas, 2006). Although livestock strategies were aimed at self-sufficiency, a general ever-increasing tendency towards a specialisation in secondary products is also detected (Franquesa *et al.*, 2000; Colominas, 2006; Colominas *et al.*, 2011). In this scenario of self-dependence, sheep emerged as the most important species for the economies of the time due to its remarkable adaptation to the Mediterranean climate, orography, and environment. Furthermore, this *taxon* provided a wide array of products, including meat, milk, wool, and manure (Miró and Molist, 1982a, b; Barbera *et al.*, 1986; Casellas, 1993; Albizuri and Nadal, 1999; Franquesa *et al.*, 2000; Rasali *et al.*, 2006; Perez *et al.*, 2007; Colominas, 2006, 2008, 2013a; Colominas *et al.*, 2019a; Valenzuela-Lamas, 2008; Nieto *et al.*, 2021). The prominence of sheep can be traced back to its initial introduction in the Iberian Peninsula during the Early Neolithic, around the VI millennium cal BC, and persisted through subsequent periods leading up to the Iron Age (Saña *et al.*, 2020; Nieto *et al.*, 2021).

In this chronotopic context, the livestock management strategies adopted by Iron Age Iberian societies have never been thoroughly investigated. Specifically, there is a lack of data regarding the three essential elements that underpin any sheep husbandry system: the reproduction patterns, the mobility strategies, and the feeding habits of the herd. The management strategies employed for these three interconnected and interdependent aspects are planned according to the technical and economic resources available in a settlement. Their purpose is to ensure the care, growth,

and maintenance of the animal (Andugar and Saña, 2004; Colominas, 2008, 2009). Hence, the exploitation of livestock and its products is not possible without their management. Livestock products include not only those that can be consumed in the short term, but also the products accumulated as reserves, those intended for commercial exchange, and the animal's use as a labour force (Andugar and Saña, 2004; Colominas, 2009). As a result, the various purposes of livestock husbandry require different management strategies, leading to a high degree of variability among different communities.

1.2 Herd management

Investigating the timing and length of the caprine lambing period is essential for fully understanding the development and organisation of ancient pastoral systems. The management of the sheep reproductive cycle has a significant impact on the availability of animal products (especially fresh milk), the workload of the farmer, and the feeding habits of the flock (Chemineu *et al.*, 2008; Balasse *et al.* 2017; Knockaert 2017; Tornero *et al.*, 2020; Walsh *et al.*, 2023). The season and seasonality of sheep birth have been the subject of increasing interest in zooarchaeological studies over the last decade. So far, a significant focus has been directed on archaeological sites in Europe and the Near East, spanning from the 6th to the 3rd millennium B.C., to shed light on the origin and early development of domestication (Tornero, 2011; Tornero *et al.*, 2016; Hadjikoumis *et al.*, 2019). These studies have revealed that human intervention in sheep populations favoured a prolongation in the duration of the birth period and, consequently, an extension of the period of sexual activity (Balasse *et al.* 2017).

Under temperate climate, sheep lambing season naturally occurs from late winter throughout spring (Hafez, 1952; Jewell and Grubb, 1974; Santiago-Moreno *et al.*, 2000; Gootwine, 2011; Gómez-Brunet *et al.*, 2012). In the absence of anthropogenic intervention, this pattern is the most common in present-day and prehistoric husbandries across temperate Europe (Balasse *et al.*, 2023). Therefore, the significant presence of autumn births necessarily indicates an extension of the natural breeding season and, as a result, a wider fertility period. Nowadays, autumn births are a common occurrence and a feature of farming systems in the Western Mediterranean region. The earliest evidence of out-of-season births traced in this area is found at the two Early Neolithic sites of Taï and Gazel, in Southern France. This demonstrates that the capability of de-seasoning births was already present, at least, in the second half of the 6th millennium BC in the Western Mediterranean (Tornerio *et al.*, 2020). The Early Neolithic sites of El Mirador and Chaves (Martín *et al.*, 2021; Sierra *et al.*, 2021), the Middle and Late Neolithic phases of Els Trocs (Tejedor-Rodríguez *et al.*, 2021), the Middle Neolithic site of Auriac (Fabre *et al.*, 2021), the Middle-Late Neolithic sites of Araguina-Sennola and Caserne de Montlaur (Fabre *et al.*, 2023), and Llo during the Middle/Late Bronze Age (Knockeart, 2017), are additional isolated cases of sites reporting autumnal lambing. Therefore, the interest in studying the reproduction patterns and demographic management of sheep employed by Iron Age Iberian communities does not lie in finding evidence of the presence of de-seasonalisation, but rather in verifying its spread and whether it was used systematically or not in this period, and whether this was linked to particular socio-economic circumstances.

Sheep mobility is a husbandry strategy adopted by communities to seek quality pastures throughout the year (seasonal altitudinal mobility, at long or short distances) or for trading purposes to reduce the inbreeding rate in a flock (unidirectional mobility; Balasse, 2014; Makarewicz, 2017; Nieto *et al.*, 2020). Investigating herd movements is essential to gain insight into livestock management in a settlement. Its organisation is strictly dependent on the timing and duration of the lambing period and on the availability of pasture and/or fodder during the year.

Mediterranean pastoral societies have long adopted seasonal altitudinal mobility to cope with unpredictable and highly variable climatic conditions (Gómez-Pantoja, 2004; Oteros-Rozas *et al.*, 2013). Indeed, the Mediterranean climate is distinguished by marked seasonal fluctuations in pasture availability and rainfall, as well as a sharp contrast between arid lowlands in the summer and snow-covered highlands during the winter (Davies, 1941; Georgoudi, 1974; Ruiz and Ruiz, 1986). Consequently, the seasonal altitudinal migration of herds allows the complementary exploitation of fresh highland pastures during the summer and warmer lowland ones during the winter (Davies, 1941; Gómez-Ibañez, 1977; Cleary, 1986; Ruiz and Ruiz, 1986). This correspondence between the herd's fodder requirements and the seasonal peaks in pasture availability ensures optimal feeding of the animals throughout the year (Ruiz and Ruiz, 1986; Manzano-Baena and Casas, 2010; Oteros-Rozas *et al.*, 2013). Seasonal altitudinal mobility emerges as a particularly well-suited livestock strategy for the ecological and orographic conditions of the Iberian Peninsula. Indeed, the presence of extensive areas with a Mediterranean climate favours the year-round

complementarity between lowland and highland areas (Ruiz and Ruiz, 1986; Gómez-Pantoja, 2004; Manzano-Baena and Casas, 2010).

Mobile pastoralism in the Iberian Peninsula has historically been mainly related to sheep husbandry and fine wool production (Blanks, 1995; Manzano-Baena and Casas, 2010; Nieto, 2016; Tornero *et al.*, 2018). This husbandry strategy reached its peak during the Middle Ages, with the official formation of the *Honrado Concejo de la Mesta* in 1273, the most prominent example of a herder organisation in the Mediterranean region. This powerful and wealthy syndicate supervised the seasonal altitudinal migration of thousands of herds between the Segovia highlands and the vast southern lowlands (Brun, 1996; Gómez-Pantoja, 2004; Oteros-Rozas *et al.*, 2012). In the north-east of the Iberian Peninsula, the organisation of a large-scale seasonal altitudinal migration system of herds dates back to the medieval period (11th-12th c.), developed by Pyrenean rural communities and major monasteries. The latter renovated the existing route network that spanned the entire territory, connecting plains, Pre-Pyrenees, and Pyrenees (Vilà i Valentí, 1991; Roigé *et al.*, 1995). This extensive network of routes follows the traces of ancient pathways, reinforced by the Roman road and bridge system (Ruiz and Ruiz, 1986; Alfaro, 2001). Indeed, during the Roman period, a long-distance trade network was consolidated in the eastern Pyrenees. These trade routes were also used by the mobile flock, connecting different grazing areas and maintaining them under tributary control (Olesti, 2022). Although there is no direct evidence of structured seasonal altitudinal mobility during Roman times, it seems unlikely that such a profitable and widespread activity attested in Italy was not also

practised in provinces with suitable climatic conditions, available land for livestock pasturing, and flocks (Gómez-Pantoja, 2001). Indeed, the earliest direct attestation of mobile pastoralism coincides with the first legal regulation of these pastoral routes with the *Fuero Juzgo*, the Visigothic code of laws, between the 6th and 7th centuries. This text includes regulations for the passage of livestock through open fields and public roads. This code of laws was compiled from prior Roman common law, suggesting the existence of a regulated and organised livestock seasonal mobility under Roman rule (Ruiz and Ruiz, 1986; Gómez-Pantoja, 2001; Gómez-Pantoja, 2004; Euba, 2008; Manzano-Baena and Casas, 2010).

Colominas *et al.* (2019b) applied geometric morphometrics to the study of size and shape variability in sheep astragali from nine archaeological sites in the eastern Pyrenees (Cerdanya) and the north-eastern Iberian coast (Empordà plain), dating from the Middle Iron Age to the Early Roman period (5th century BC - 3rd century AD). The results obtained were combined with data-sets from Number of Identified Specimens (NISP) and slaughtering patterns from traditional zooarchaeological studies. According to Colominas and colleagues, data from the Roman period reveal a congruence in astragali size and morphology between sites located in mountainous and coastal regions, as well as the implementation of similar husbandry practices. This evidence would suggest the existence of a connection between the two areas, involving a shared orientation in the exploitation of sheep and possible seasonal altitudinal movements of the herds. On the other hand, during the Middle Iron Age, there was a clear distinction in size and husbandry strategies between the herds raised in the mountain sites and

those bred by the Iberian communities along the lowland coast. The local character of the livestock practices and the presence of different sheep populations between the two areas during this period would suggest few livestock connections between mountain and coastal communities. Therefore, regular livestock movements from the lowland coast to the Pyrenees and vice versa would have occurred for the first time during the Roman period. Indeed, under Roman rule, increasing anthropogenic pressure on the local landscape would have made the migration of livestock to ecologically complementary areas necessary for their feeding (Nolla *et al.*, 2010; Colominas, 2019b).

In two previous studies, Valenzuela and colleagues (2016, 2018) conducted strontium isotopic analyses on sheep and goat teeth recovered from the site of Turó de la Font de la Canya (Barcelona), dated between the 7th and 2nd centuries BC. The obtained strontium values are quite homogeneous and do not indicate any evidence of long-distance seasonal mobility, suggesting that Iron Age communities in the north-eastern Iberian Peninsula practised limited-scale husbandry.

Investigating the feeding habits of past herds is essential for reconstructing their breeding, maintenance, and exploitation. Traditionally, livestock feeding strategies are determined based on the environmental characteristics of the available territories for herders. Additionally, animal feeding often follows a seasonal pattern, depending on the availability of pastures or shifting between complementary areas, since grass is the most economical and least labour-intensive nutrient source (Andugar and Saña, 2004; Walsh *et al.*, 2023). Nevertheless, alternative

strategies could be employed to feed the herds. One option is the exploitation of forests and less productive lands, where the herds would consume leaves and fine branches (Halstead, 1996). Integration with the agricultural calendar is also a crucial possibility. Indeed, cereals can be introduced to the livestock's diet in the form of fodder or forage to compensate for seasonal shortages of pasture. Other agricultural waste, such as the leaves and bark of pruned trees, almonds, olives, vines, walnuts, or fig trees could also be used to produce fodder (Forbers, 1998). Hay is another example of fodder, involving the storage and drying of the selected plants to maintain their nutritional value (Lavin *et al.*, 1993).

These different feeding strategies can be combined or used individually. Each of them has different labour implications for shepherds, which imply a different organization of the whole community and a distinct exploitation of the environment. Finally, herd nutrition is also closely linked to the reproduction cycle, with females and males having different nutritional needs on a seasonal basis (Andugar and Saña, 2004; Balasse, 2014). Likewise, young individuals require special care and attentive feeding.

Therefore, adapting livestock feeding habits to the different ecological contexts of the north-eastern Iberian Peninsula, to their economic necessities, and ensuring access to vegetable resources throughout the year must have been challenging for Iron Age Iberian herders. An investigation into the feeding strategies adopted by each community is therefore essential to understanding livestock breeding, management, and exploitation in this chronotopic context.

This PhD project investigates for the first time the livestock management strategies (the whole areas of interest: reproduction, mobility, and feeding patterns on animals) adopted by Iron Age Iberian societies through a biogeochemical approach (isotope analyses) on faunal remains, specifically sheep teeth and bones. As previously reported, the latter was the most important species for the economy of this period.

1.3 Integrating isotope analyses on zooarchaeological research

Since the mid-1970s, isotope analyses have been increasingly applied to archaeological research. They provide valuable information on the isotopic composition of archaeological remains, especially on organic materials (Tykot, 2004; Tornero and Saña, 2006; Tornero, 2011; Moffat, 2014). These biogeochemical analyses are mainly employed to infer environmental characteristics, feeding habits, mobility patterns, raw material supply, trade and commerce, and the management of agricultural and husbandry production (Cruells *et al.*, 2006; Moffat, 2014).

Most of the palaeozootechnical data may be inferred from the study of the isotopic composition of animal bones and teeth. Oxygen ($\delta^{18}\text{O}$), carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$), and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) are the most commonly stable isotope ratios used for this purpose. Their isotopic composition is mainly related to the environment (climate, geology, vegetation cover) and the physiology of plants and animals (metabolism, how signals are recorded in tissues), of which they provide direct information (Balasse, 2006, 2014; Tornero and Saña, 2006).

Biogeochemical data and stable isotope analyses have proven to be fundamental tools for complementing and enriching traditional zooarchaeological studies reconstructing past husbandry strategies. Their contribution is particularly important for inferring past husbandry strategies, providing data on reproduction patterns, mobility strategies, and feeding habits of livestock (Balasse, 2006, 2014; Tornero and Saña, 2006), among other aspects. This information is obtained through, although not only, the sequential analysis of tooth enamel and the bulk analyses of bones.

At medium and high latitudes, husbandry practices are strongly influenced by the seasonal cycle, which determines both the availability of plant and water resources and the biological cycle of animals (Balasse, 2006, 2014). With seasonal time-scale resolution, serial sampling of sheep molar enamel provides innovative life-history data about past herds, potentially inferring birth season and seasonality and lambing period, flock's movements, and diet. On the other hand, studies involving bulk analysis of bones provide valuable information on livestock feeding (Balasse, 2002, 2006). Therefore, isotope analyses on faunal remains allow the direct detection of phenomena on precise temporal and spatial scales that are impossible to detect with traditional zooarchaeological analyses (Balasse, 2006; Cruells *et al.*, 2006).

This doctoral research investigates the husbandry strategies adopted by Iron Age Iberian communities in the north-east of the peninsula through multi-stable isotope analyses of domesticated and wild animals recovered from four relevant Catalan sites: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira.

1.4 Principles: stable isotopes and herding strategies

Dental enamel is composed of 98% mineral fraction (i.e. hydroxyapatite or bioapatite compound) and the remaining 2% organic fraction (Lee-Thorp, 1989; Koch *et al.*, 1997; Balasse, 2002e). Bioapatite mostly consists of large apatite crystals, which make the enamel very dense and tough (Koch *et al.*, 1997; Hillson, 2005). This makes teeth less susceptible to alterations during the diagenesis process and, therefore, particularly suitable for stable isotope analysis (Lee-Thorp and Van der Merwe, 1987; Lee-Thorp, 1989; Ayliffe *et al.*, 1994; Bryant *et al.*, 1994; Wang and Cerling, 1994; Fricke and O'Neil, 1996; Passey and Cerling, 2002; Balasse, 2002). Primarily, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and $^{87}\text{Sr}/^{86}\text{Sr}$ values can be measured in dental enamel bioapatite (Koch *et al.*, 1997).

Bone tissue comprises 30% organic fraction, mostly collagen protein, and 70% inorganic, bioapatite (Herring, 1976; Miller, 1984; Krueger, 1991; Koch *et al.*, 1997; Copley *et al.*, 2004). After an individual death, the process of bone degradation advances and collagen, the protein that is best preserved in bone tissue, begins to decompose (Hedges *et al.*, 2004). For this reason, collagen is rarely preserved in fossil remains prior to 50ka BP. Furthermore, arid or humid environments and contexts with strong seasonal contrasts accelerate its degradation (Wang and Cerling, 1994; Weiner and Bar-Yosef, 1990; Hedges *et al.*, 2004; Tykot, 2004; Buckley & Collins, 2011). Isotope analyses of bone collagen have mainly focused on measuring $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

1.4.1 Dental enamel isotope analysis

Tooth enamel does not remodel once mineralised. As a result, the mineral fraction of the enamel reflects the isotopic signature recorded during its formation. In sheep, the crown formation of the second molar (M_2) begins between the first and second month of life and is completed at 12 months. On the other hand, the third molar (M_3) starts forming from the tenth month onwards and is completed at around 22 months (Milhaud and Nézit, 1991; Hillson, 2005; Zazzo *et al.*, 2010). Each of the two molars provides insight into one year of an individual's life. The information obtained from the combination of the two molars allows for tracing back the first two years of a sheep's life.

The oxygen isotope composition measured in tooth enamel bioapatite is mainly derived from ingested water and consumed plants (Longinelli, 1984; Luz *et al.*, 1984). These isotopic signatures are well-related to the meteoric water and temperature fluctuations, which vary seasonally in temperate latitudes. As a result, at medium and high latitudes, higher $\delta^{18}\text{O}$ values indicate the warmer season, whilst lower $\delta^{18}\text{O}$ values occur during the coldest one (Gat, 1980).

The sequential series of the $\delta^{18}\text{O}$ values recorded along each tooth crown allows the inference of the season and seasonality of sheep birth and the duration of the lambing period. Indeed, similar sinusoidal variations of warm and cold episodes among different sampled specimens would indicate synchronised births, whilst divergences may indicate different birth seasons. However, variations in dental crown height between individuals

affect the sequential $\delta^{18}\text{O}$ series and inter-individual variability (Balasse *et al.*, 2012). Therefore, to compare the placement of oxygen sequences between individuals, it is necessary to eliminate the bias associated with the variability in tooth size by normalising the distances (Knockaert, 2017). Balasse and colleagues (2012) proposed a method for modelling the sequences, enabling an objective description and comparison of the acquired archaeological data (Tornero *et al.*, 2013). However, to infer an individual's season of birth, it is necessary to consider the delay in enamel mineralisation, which affects the recording of the isotopic signal in the crown (Balasse *et al.*, 2012). For this reason, it is indispensable to use modern sheep populations with known birth seasons. These references provide a framework for placing the birth seasons of archaeological individuals within an annual calendar, facilitating the interpretation of births distribution within past societies' herds (Knockaert, 2017). Currently, reference data are available for both M_2 and M_3 . However, a higher inter-individual variability in the timing of M_3 formation has been observed, resulting in a lower resolution when defining the birth calendar.

This research assesses seasonal reproduction patterns following Balasse *et al.*, 2003, 2012, and Tornero *et al.*, 2013. To quantify the inter-individual variability in tooth size and determine the position of the maximum $\delta^{18}\text{O}$ value in the tooth crown (x_0/X), the $\delta^{18}\text{O}$ sequences have been modelled using the equation described by Balasse *et al.*, 2012, based on a cosine function (Figure 1). The model comprises four parameters for M_2 modelling: the period of the cycle (X), expressed in mm and corresponding to the length of tooth crown potentially formed over

a year; the amplitude of the isotopic signal (A), expressed in ‰; the delay (x_0) expressed in mm, corresponding to the position in tooth crown where the $\delta^{18}\text{O}$ has his maximum value; and the mean (M), expressed in ‰. For the modelling of M_3 , four additional parameters have been introduced: the slope of the mean (p), expressed in mm; the signal attenuation (x_A) and the lateral shift (x_B) of the amplitude, both expressed in mm; the gradation of the period (b). With the inclusion of parameter b , the normalised period for M_3 is given by x_0/X_{real} . As the inter-variability in (x_0/X) reflects the variability in the birth season, this latter has been estimated by comparison with the reference data including individuals from Blaise and Balasse, 2011, Balasse *et al.*, 2012, Balasse *et al.*, 2017, Balasse *et al.*, 2020, Balasse *et al.*, 2023, and Tornero *et al.*, 2018.

$$\delta^{18}\text{O}_m = Ae^{\left(\frac{x-x_B}{x_A}\right)} \cos\left(2\pi \frac{x-x_0}{X+bx}\right) + M + px$$

Figure 1 Cosine function by Balasse *et al.*, 2012.

The $\delta^{13}\text{C}$ values measured in dental bioapatite are related to the carbon isotopic composition of the plants ingested by an individual (Lee-Thorp and van der Merwe, 1987). This mainly varies according to the photosynthetic pathway of the plants (i.e. C_3 and C_4), although it can also be influenced by growing conditions and other factors (Bender, 1971; Farquhar *et al.*, 1989). The expected average $\delta^{13}\text{C}$ value for C_3 plants is -28.5‰, ranging from -20‰ to -37‰. On the other hand, $\delta^{13}\text{C}$ values above -23‰ are related to C_4 plants, with an average value of -13‰. Extremely low $\delta^{13}\text{C}$ values indicate exclusive consumption of plants grown in closed-canopy forests, with a cut-off of -31.5‰ (Tieszen & Button, 1988; Tieszen, 1991; Kohn, 2010). These values have been calculated

in modern plants, whereas those from the pre-industrial era require a +1.5‰ correction to compensate for the fossil fuel effect (Friedli *et al.*, 1986; Marino and McElroy, 1991; Feranec and MacFadden, 2006). Large ruminant mammals exhibit an isotope enrichment (ϵ^*) of $14.1 \pm 0.5\text{‰}$ between diet and enamel bioapatite (Cerling and Harris, 1999).

C_3 plants, typical of temperate environments, generally dominate the vegetation of Western Europe. On the other hand, wild C_4 plants are either inexistent or residual in temperate environments, with any presence confined to lowland areas (Mateu, 1992; Pyankov *et al.* 2010). Therefore, the eventual presence of C_4 plant intake by livestock in the studied chronotopic context suggests the consumption of cultivated C_4 plants, such as millet (*Panicum milliaceum*) and foxtail millet (*Setaria italica*). In the Iberian Peninsula, the earliest evidence for millet dates to the 3rd millennium BC at the Portuguese site of Castro de Palheiros, whilst the earliest trace of foxtail millet comes from the Kobaederra cave (Basque Country), from a level dated to 3310-2900 cal BC (Figueiral, 2008, 2017; Zapata, 2002; Moreno-Larrazabal *et al.*, 2014). Thus, the first appearances of C_4 cereals in Iberian territory are traced back to the Bronze Age, with a full spread of their cultivation occurring during the Late Bronze Age and Iron Age (Moreno-Larrazabal *et al.*, 2014; Teira-Brión, 2022; Alonso and Pérez-Jordà, 2023). An early presence of different millets is found in the coastal area of north-eastern Catalonia, where millet and foxtail millet are documented at the Sant Martí d'Empúries site in a phase dated from 850 to 800 BC (Buxó, 1999; Alonso and Pérez-Jordà, 2023). Millet would have been introduced into this area from southern France, through

the Pyrenees (Moreno-Larrazabal *et al.*, 2014; Alonso and Pérez-Jordà, 2023).

Generally, C_3 plants grown in dry environments tend to have higher $\delta^{13}\text{C}$ values than those adapted to humid conditions. This is due to their greater water use efficiency. Conversely, plants grown in humid environments display lower $\delta^{13}\text{C}$ values (Farquhar *et al.*, 1989; Friend *et al.*, 1989; Körner *et al.*, 1991; Kohn, 2010). Furthermore, $\delta^{13}\text{C}$ values slightly increase along altitudinal gradients as a result of the decrease in CO_2 pressure on $\delta^{13}\text{C}$ (Körner *et al.*, 1991). In addition, seasonality moderately influences the $\delta^{13}\text{C}$ values of C_3 plants, with the highest values occurring during the warmest and driest seasons and the lowest values during the coldest and wettest seasons (Smedley *et al.*, 1991; Diefendorf *et al.*, 2010; Hartman and Danin, 2010).

Drawing upon these principles, the isotopic signatures incorporated into sheep molar enamel from the food and water ingested provide insights into the environmental conditions in which the animals lived and how these changed during their lifespans (Balasse and Ambrose, 2005; Tornero *et al.*, 2018). Following this premise, livestock mobility can be detected by, but not only, the inverse relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values along the sequential dental series, as originally proposed in Tornero *et al.* (2016, 2018). Indeed, the negative co-variation of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences along the tooth crown provides evidence for seasonal altitudinal mobility of livestock between pastures with distinct meteoric waters and vegetation. In this way, individuals grazing at higher altitudes during the summer months return a sequence with the highest $\delta^{13}\text{C}$ values corresponding to the lowest $\delta^{18}\text{O}$ values. In contrast,

individuals grazing at lower altitudes during the winter months exhibit a sequence where the lowest $\delta^{13}\text{C}$ values coincide with the highest $\delta^{18}\text{O}$ values. To interpret the archaeological data in this study, modern reference data presented in the works of Knockaert *et al.* (2018) and Tornero *et al.* (2018) are used as baselines. Both of these cited studies were conducted in the Pyrenees Mountains, the closest elevated locations to the archaeological sites where samples were recovered. These are the only two available experimental studies in the study region.

Strontium isotope ratios can provide evidence of mobility across territories with different geological substrates. This is because the geochemical signature of strontium isotopes is directly related to the geology of the area where an animal acquires food. Radioactive rubidium (^{87}Rb) decays into ^{87}Sr over time and, consequently, the $^{87}\text{Sr}/^{86}\text{Sr}$ values in rock minerals vary depending on their original Rb/Sr content and geological age (Ericson 1985; Beard and Johnson 2000; Price *et al.* 2002). $^{87}\text{Sr}/^{86}\text{Sr}$ is not subject to 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 (Ericson 1985; Beard and Johnson 2000; Price *et al.* 2002). Thus, the strontium isotope compositions of the bioapatite reflect the signatures of the geological area where the individual resided and fed during the mineralisation of dental enamel (Beard and Johnson 2000; Price *et al.* 2002; Madgwick *et al.* 2012). As a result, possible herd movement during the developmental period between two locations with a measurable strontium isotope difference can be traced (Montgomery 2010).

This study investigates sheep movements across different altitudinal and geological areas during protohistoric periods by combining $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequential analysis with $^{87}\text{Sr}/^{86}\text{Sr}$ measurements in the same dental series. At the same time, the effectiveness of integrating these proxies is tested. This approach has been successfully applied before (Balasse *et al.*, 2002; Bentley and Knipper, 2005; Viner *et al.*, 2010), especially in contexts where complex orogenic areas are absent. Moreover, relying on the results of $^{87}\text{Sr}/^{86}\text{Sr}$ analyses enables the determination of the reason behind the increase in $\delta^{13}\text{C}$ values in an individual during winter. Indeed, this may be produced either by a change in the pasture due to altitudinal movement or by integrating C_4 plants into the diet. Evidence of domesticated C_4 plants such as millet and foxtail millet has been identified in almost all the settlements studied in this doctoral thesis (Canal, 2000, 2022; Colominas *et al.*, 2023; Riera *et al.*, 2020). Consequently, their eventual use as livestock fodder during winter would overshadow the seasonal mobility signals displayed by the inverse relationship between the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sequences. Substantial variations in $^{87}\text{Sr}/^{86}\text{Sr}$ are explored at an intra-individual level in correspondence with the inverse relationship of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences. These variations serve as evidence of a change in pasturage, indicating in-life mobility.

1.4.2 Bone collagen analysis

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic values from bone collagen provide a quantitative assessment of the protein components of an individual's diet. These values correspond to the average food intake over the last 10-15 years of life. This duration is approximately the time

required for bone collagen to remodel itself during an individual's lifetime (Ambrose, 1986; Tykot, 2004; Hedges *et al.*, 2007). The isotopic signatures recorded in animal tissue differ from those of the initial source consumed due to isotopic fractionation. The carbon isotopic fractionation between dietary intake and the consumer is about +5‰, while it amounts to about +1‰ from dietary collagen to collagen consumer along the trophic chain (DeNiro and Epstein, 1978; Schoeninger and DeNiro, 1984; Ambrose and Norr, 1993; Bocherens and Drucker, 2003). On the other hand, the nitrogen isotopic fractionation is between 3-5‰ at each trophic step (Minagawa and Wada, 1984; O'Connell *et al.*, 2012; Matsubayashi and Tayasu, 2019).

The carbon isotope value measured in bulk collagen derives from the isotopic composition of plants ingested by an individual. Therefore, it allows differentiation between C₃ and C₄ plant consumption. Moreover, the $\delta^{13}\text{C}$ isotopic signature in collagen also permits the discrimination between a diet primarily comprised of terrestrial or marine foods. Indeed, marine plants exhibit higher values of carbon as well as nitrogen (Richards and Hedges, 1999; Tykot, 2004; Fisher *et al.*, 2007).

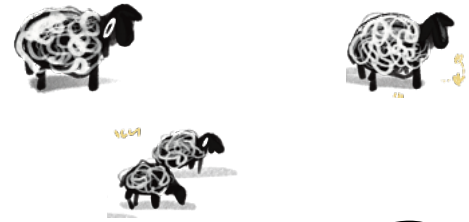
The nitrogen isotope value in terrestrial plants mainly depends on the type of nitrogen obtained and how it is absorbed from the substrate. This can occur through fixation mediated by symbiotic microbes or directly from soil nitrates (Katzenberg, 2018; Evans, 2001; Tykot, 2004; Szpak, 2014). Furthermore, soil nitrogen enrichment can vary as a result of both natural factors (substrate type, degree of soil development, nutrient availability, mycorrhizal associations, soil associations, climate) and anthropogenic ones (i.e. manuring;

Bogaard *et al.*, 2007; Szpak, 2014; Jordana *et al.*, 2019; Makhad *et al.*, 2022). The $\delta^{15}\text{N}$ values measured in collagen are used to determine the trophic level of an individual within the food web. Specifically, an isotopic signature enriched in nitrogen corresponds to a higher intake of animal protein. Consequently, predators exhibit $\delta^{15}\text{N}$ isotope values higher than those of their prey (DeNiro and Epstein, 1978; Schoeninger and DeNiro, 1984; Katzenberg, 2018). However, when comparing individuals from different ecosystems, it is important to consider the isotopic composition of the local food web (Katzenberg, 2018; O'Connell *et al.*, 2012). For this reason, creating a local baseline is essential for accurately interpreting the nitrogen isotope values of each sampled individual.

UNIVERSITAT ROVIRA I VIRGILI

TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC) : A MULTI-ISOTOPE RESEARCH

Chiara Messina



Research objectives

2

2.1 Research Aim

Traditional zooarchaeological studies have yielded information on husbandry and livestock exploitation during the Middle/Late Iron Age in the north-east of the Iberian Peninsula. However, data on the in-life livestock management by Iberian communities is extremely very limited or non-existent. Information on livestock management strategies, especially for economically relevant livestock species, is an essential way to comprehend the technological, economic, and cultural development of Iron Age Iberian communities and their relationship with the environment. This doctoral thesis aims to address this lacuna providing, for the first time, an in-depth insight into the livestock management strategies adopted by Iron Age Iberian communities. Specifically, we decided to focus our research on sheep, the most important species for the economy during this period. As previously stated in Section 1.1, sheep's great adaptability and the wide variety of products this species provides led to its predominance in the chronotopic context investigated in this thesis.

2.2 Specific Objectives

The research was articulated into three specific objectives to achieve a comprehensive overview of the topic, reflecting the three core elements of any livestock system, as presented in the introduction chapter (see Sections 1.1 and 1.2).

I. Reproduction patterns: The first objective aims to determine the extent of human control over the sheep's reproductive cycles. The season and seasonality of births and the duration of the lambing period are inferred.

II. Mobility strategies: The second objective focuses on effectively tracing eventual herd movements across different altitudinal and geological areas, outlining the pastoral strategies adopted by Iron Age Iberian communities.

III. Feeding habits: The purpose of the third and final objective is to detect changes induced by Iberian shepherds in sheep diets and the possible seasonal supplements in their diet.

2.3 Setting the stage

To achieve the general objective of this doctoral dissertation, we selected four Middle/Late Iron Age sites from the north-eastern Iberian Peninsula that featured the most suitable contexts for employing different livestock management strategies in relation to the climate and environment, the availability of pasture and fodder throughout the year, and the social structure of the settlements.

The selected faunal remains proceed from four archaeological sites with contemporaneous and well-dated occupations along the 3rd century BC. All settlements are located in distinct ecological and cultural areas in the north-east of the Iberian Peninsula. Mas Castellar de Pontós is situated on a fertile plain in the northern pre-coastal area, in the territory of the *Indigeti*. Ascending to higher altitudes is the *Ceretan* settlement of Tossal de Baltarga, on the Cerdanya plain, in the Catalan Pyrenees. Moving inland, the Pre-Pyrenean area hosts the settlement of Sant Esteve d'Olius, in the fertile *Lacetan* agricultural plain. Lastly, near the central Mediterranean coast, the *Laietan* site of Turó de la Rovira stretches across the Barcelona plain.

The four sites are open-air settlements located along three of the main and oldest traditional pastoral routes converging in the Eastern Pyrenees. For this reason, they are particularly well suited to bear witness to the herds' movements from winter pastures in the lowlands to summer pastures in the highlands.

Agriculture, and specifically cereal production, has traditionally been considered the main economic activity in all four settlements. Indeed, the management, production, storage, and distribution of agricultural surpluses

have been documented (Pons *et al.*, 2010; Morera, 2017; Asensio *et al.*, 2008). Three of the sites, except for Tossal de Baltarga, have revealed archaeological evidence of silo fields. However, the *Ceretan* settlement has preserved large ceramic containers and concentrations of wheat grain in one of its buildings, suggesting a probable storage function (Olesti *et al.*, 2018). The presence of domesticated C₄ plants, such as millet (*Panicum milliaceum*) and foxtail (*Setaria italica*), is attested in almost all the settlements here studied (Canal, 2000, 2022; Colominas *et al.*, 2023; Riera *et al.*, 2020).



Materials and methods

3

3.1 The archaeological sites

- Mas Castellar de Pontós

Mas Castellar de Pontós is situated in the Empordà region (Girona, 154 m a.s.l.; *Figure 3.1*) on a headland flanked by two watercourses. The site is located approximately 17 km equidistant from the Greek colonies of *Rhode* and *Emporion*, near the Mediterranean coast. Its favourable geographical location made it a strategic communication nexus, facilitating connections between the coastal and inland regions and fostering interactions between the two Greek colonies and the indigenous inhabitants (Pons *et al.*, 2010). The human occupation of the settlement spans a broad chronological spectrum, covering from the late 7th century BC to the early 2nd century BC (Adroher and Pons, 2002; Pons *et al.*, 2010). The phase investigated in this study extends between 250 BC and 180 BC. During this time frame, the site hosted a specialised agricultural settlement associated with an extensive silo field (Pons *et al.* 2010). Governed by a rural aristocracy, the rural settlement assumed a crucial role as a commercial enclave for cereal

production and operated as a reserve centre for the *Emporion* area (Bouso *et al.*, 2000; Fuertes *et al.*, 2002).

The anthracological analyses carried out at the Mas Castellar de Pontós site reveal the presence of mixed holm oak and sessile oak woodlands (*Quercus ilex* and *Quercus petraea*) in the area surrounding the rural establishment, along with the additional presence of juniper (*Juniperus* sp.) and silver fir (*Abies alba*). Moreover, evidence attests to a riparian vegetation ecosystem (*Alnus* and *Ulmus*), characteristic of the marshy Empordà plain, an area rich in ponds and wetlands (Ros and Piqué, 2002). The carpological data provide evidence of a great variety of crops, including both winter varieties (wheat and emmer) and spring types (millet, foxtail millet, barley, oats). Barley and millet emerge as the predominant cereals, with the latter being the only C₄ plant alongside foxtail millet cultivated within the settlement. In addition to these cereal crops, the agricultural practices at the site included the cultivation of legumes (peas, lentils), albeit in minor quantities. These leguminous crops

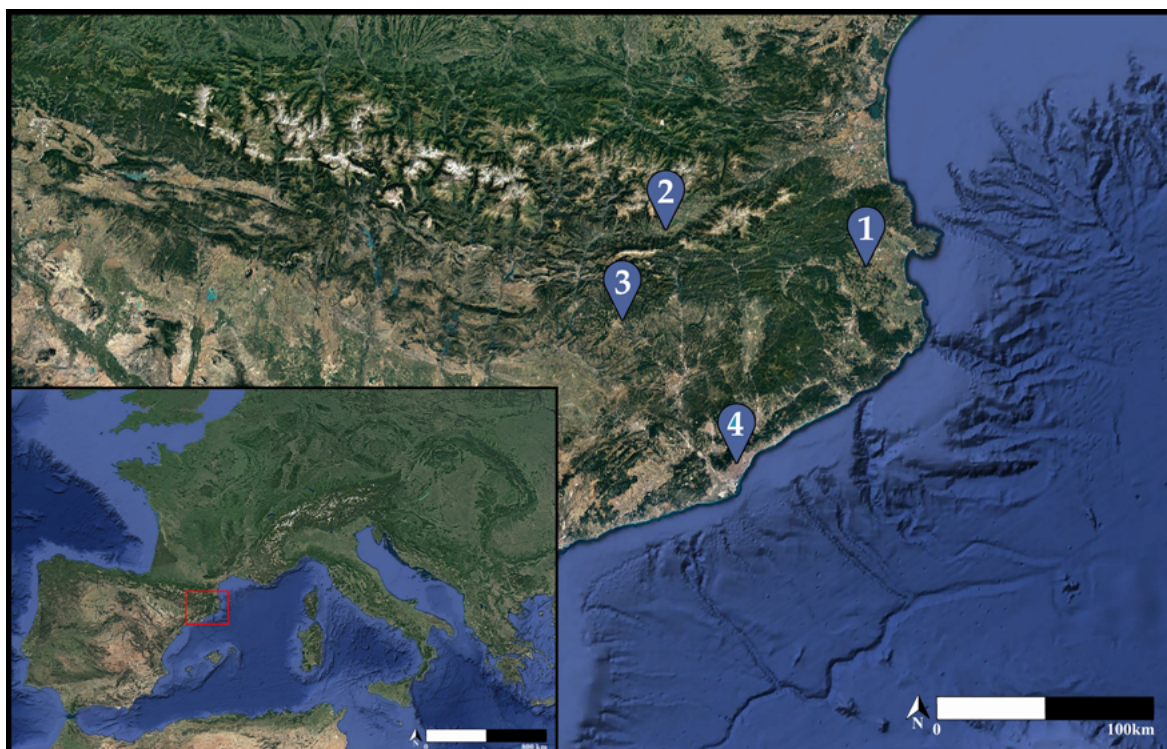


Figure 3.1 Geographical location of the four archaeological sites included in this research: (1) Mas Castellar de Pontós, (2) Tossal de Baltarga, (3) Sant Esteve d'Olius, and (4) Turó de la Rovira (Google Earth Pro modified).

contribute to nitrogen fixation in the soil, maintaining a high fertility level and provide a valuable source of high protein content (Khan *et al.*, 1979; Phillips, 1980; Boulter, 1982; Ladd *et al.*, 1986; Hulse, 1989; Dakora and Keya, 1997; Rochester *et al.*, 2001; Iqbal *et al.*, 2006; Liu *et al.*, 2011; Yuvaraj *et al.*, 2020). Among fruit-bearing trees, vines and, to a lesser extent, olive trees are also present (Canal, 2000; Canal, 2002). The cereal production at Mas Castellar de Pontós likely involved diverse strategies for intensive crop management, incorporating both rotation systems (biennial and triennial) and the concurrent sowing of different species, such as foxtail millet and barley (Alonso, 2000; Canal, 2000).

The recovered fauna remains reveal a strong predominance of domestic species (99% of recorded remains). Among these, caprines emerge as the most represented group (51%), with sheep being the predominant

species, followed by cattle (25%) and pigs (16%). Hunting activities were occasional and had a minimal impact on the overall human diet (Colominas, 2013a). Nonetheless, the few remains of deer, wild boar, and rabbit confirm the proximity of wooded areas interspersed with pastures. Regarding sheep husbandry, the prevalent occurrence of adult and old individuals suggests intensive exploitation of secondary products (i.e., milk and wool; Colominas, 2008; Colominas, 2013a).

- Tossal de Baltarga

The high mountain site of Tossal de Baltarga (Bellver de Cerdanya, 1166 m a.s.l.; *Figure 3.1*) is located in the eastern Catalan Pyrenees. The primary purpose of the settlement was to exercise territorial control over the communication routes that crossed the

Cerdanya plain (Colominas *et al.*, 2023). The archaeological excavation of the site has revealed three different phases of occupation spanning from the late Bronze Age to the Republican Roman period (Morera, 2017). During the Iron Age phase (4th - 3rd century B.C.) Tossal de Baltarga played a relevant social and economic role within the *Ceretan* population. Towards the end of the 3rd century BC, the settlement, organised into several residential and working buildings, was violently destroyed by fire (Morera, 2017; Colominas *et al.*, 2023).

The majority of the archaeobotanical and faunal remains recovered come from one of the buildings (G). Here, the anthracological analysis identified charcoal remains of *Pinus sylvestris/nigra* as the primary *taxon*, along with *Albies alba*, and *Rosaceae/Maloideae* (Colominas *et al.*, 2023). Although limited, the carpological remains attest to the presence of barley (*Hordeum vulgare*), wheat (*Triticum aestivum/durum/turgidum*), millet (*Panicum miliaceum*), and einkorn (*Triticum monococcum*). However, the majority of macrobotanical remains belong to wild plants (Colominas *et al.*, 2023). The analysis of phytoliths supports these data, with the majority of them being derived from monocotyledonous plants, particularly grasses and weeds of the *Pooideae* subfamily (Colominas *et al.*, 2023). The Iberian period witnessed an increase in agricultural production in the Cerdanya plain, favoured by a generally dry climate complemented by abundant water sources (Morera, 2017; Olesti and Mercadal, 2017). Consequently, during the 3rd century B.C., Cerdanya likely appeared as a plain characterised by an agrarian landscape bordered by forest vegetation essentially consisting of coniferous forests (pine and silver fir), which dominated the mountain area.

Building G provided the remains of four sheep, a goat, and a horse from a separate space. As a result, the shepherds from Tossal de Baltarga likely engaged in partial or complete controlled stabling of livestock (Morera *et al.*, 2017). All individuals were sub-adults or adults at the time of death caused by the fire. The mortality profiles thus indicate a focus on the products derived from the animals during their lifetimes rather than on their meat (Colominas *et al.*, 2023). This implies a significant investment of time and care in these animals by the settlement's inhabitants to exploit them. Remains of cattle and pigs were recovered in other buildings, attesting their presence and exploitation within the settlement (Olesti *et al.*, *submitted*).

- Sant Esteve d'Olius

The Sant Esteve d'Olius site (Solsonès, 664 m a.s.l.; Figure 3.1) was a small village located in the fertile *Lacetan* plain. The settlement was strategically situated on the highest point of a small promontory, within the Pre-Pyrenees area, inland in the Catalan region. The area was bordered by the river Cardener, the principal communication way to the coast (Asensio *et al.*, 2003b, 2008). The site was occupied during Medieval and Iron Age times. During the Iron Age phase (3rd c. BC), it assumed prominence as a fortified settlement specialised in the storage and management of cereal surpluses, with silo fields and residential buildings (Asensio *et al.*, 2003b; Chorén and Calduch, 2006; López, 2009). The centrality of agricultural activities is evidenced by the silo field areas surrounding the site. These areas outnumber and exceed the designated residential zones and act as a pole of attraction for the neighbouring communities. The

expansive and fertile plain irrigated by the river Cardener probably played a crucial role in the development of these agricultural activities (Asensio *et al.*, 2008). Although these types of strategic nuclei specialised in the storage of cereal crops are well known along the Iberian Mediterranean coastal zones, their presence in inland locations, as in the case of Sant Esteve d'Olius, is exceptional (López, 2009).

The archaeobotanical data from the silos revealed a significant production of cereal crops, particularly the winter varieties: barley and, in less proportion, wheat and emmer. Furthermore, there is limited evidence of leguminous plants, such as peas and lentils (López, 2009). Among wild plants, species of the *Rubiaceae* family are the most frequently attested, including catchweed bedstraw or stickwilly (*Galium aparine*, *Galium* sp.), as well as woodruff (*Asperula* sp.) and white bedstraw (*Galium* cf. *mollugo*) in minor quantities. Weedy grasses associated with winter cereals, such as oats (*Avena* sp.), darnel or ryegrass (*Lolium* cf. *temulentum* and *Lolium* sp.) and timothy (*Phelum* sp.) are also present, in addition to other pluvial weeds like *Lithospermum* sp. Additionally, the archaeological record includes evidence of collected fruits, such as sloe berries (*Prunus spinosa*) and an acorn (*Quercus* sp.; López, 2009).

The analysis of zooarchaeological remains reveals the predominance of domestic mammal remains. Caprines are prevalent, with sheep more frequent than goats, followed by pigs and cattle (Colominas 2013b). Hunting constituted a secondary activity with limited impact on the human diet. The presence of wildlife remains such as deer, badger, *Leporidae*, fox, beech marten, amphibians, and fish confirms the proximity of watercourses and a wetland environment and attests to the presence of wooded areas near the

settlement. The mortality profiles of sheep indicate a primary focus on the exploitation of meat and, secondarily, wool and milk (Colominas, 2013b).

- Turó de la Rovira

The fortified settlement of Turó de la Rovira dates back to the mid-3rd century BC and was occupied until the late 3rd/early 2nd century BC. It is located on the Barcelona plain, on the top of a small promontory near the Mediterranean coast (Barcelonès, 262 m. a.s.l.; Figure 3.1; Colominas i Roca, 1954; Giner, 2018). The settlement has been interpreted as a second-order village of the *Laietan* territory, occupying a dominant position over the neighbouring minor centres during the Iron Age (Giner, 2018). Archaeological research has revealed a set of residential buildings on the southern slope, complemented by two silo field areas concentrated on the two sides of the village. The settlement was delimited by a wall and featured a moat on the south-eastern side (Giner 2018).

Anthracological studies attested to the dominance of open-landscape surroundings, with abundant remains of strawberry tree (*Arbutus unedo*), holm oak/kermes oak (*Quercus ilex/coccifera*), and heather (*Erica* sp.). Deforestation was intense, probably due to the presence of cultivated fields in the surrounding area (Riera *et al.*, 2020). Carpological data indicates the predominance of wheat and barley, with legumes, grapes, and figs present in smaller quantities. Interestingly, the study also documents the presence of millet, although in small amounts (Riera *et al.*, 2020).

The majority of the faunal remains come from silos with similar chronology and homogeneous content of carpological remains (Riera *et al.*, 2020). Caprines are the most attested *taxon*, with sheep

slightly outnumbering goats. They are followed by pigs and cattle and, in minor numbers, equids, dogs, and *Leporidae*. Among sheep, adults prevail, indicating their exploitation for meat and wool (Colominas, 2019a).

3.2 Faunal materials

A total of 74 archaeological remains (31 teeth, 43 bones) belonging to 51 sheep (*Ovis aries*, Linnaeus, 1758) from the four Iron Age Iberian settlements mentioned above were studied for this doctoral research. *Table 3.1* presents information on the 51 sheep individuals, including their provenance site, the elements sampled and analysed, the age category, and the analysis performed.

The sequential $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotope analyses were conducted on 31 lower molars (18 M_2 and 13 M_3) belonging to 22 sheep. Among these, 12 teeth (seven M_2 and five M_3) from seven individuals were selected for strontium isotope analysis. Ten M_2 and seven M_3 were recovered from mandibles, while the remaining were isolated teeth. All molars selected for the analyses showed entirely or almost fully formed crowns and early wear stages. From Mas Castellar de Pontós, 21 remains (10 teeth, 11 bones) from 16 sheep were analysed; 10 remains (five teeth, five bones) from six sheep came from Tossal de Baltarga; from Sant Esteve d'Olius, 27 remains (10 teeth, 17 bones) from 19 sheep were studied; and finally, 16 remains (six teeth, 10 bones) from 10 sheep were analysed from Turó de la Rovira.

In addition, 153 bones from the other main domestic and wild species were analysed to establish the local isotopic baseline of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for each settlement. *Table 3.2* reported the provenance site, the *taxon*, the element analysed, and the age category of each

selected bone. From Mas Castellar de Pontós, five goat remains (*Capra hircus*, Linnaeus, 1758), six cattle (*Bos taurus*, Linnaeus, 1758), four pigs (*Sus scrofa domesticus*, Linnaeus, 1758), five horses (*Equus caballus*, Linnaeus, 1758), five dogs (*Canis familiaris*, Linnaeus, 1758), three birds (including one milvus, *Milvus milvus*, Linnaeus, 1758), and six rabbits (*Oryctolagus cuniculus*, Linnaeus, 1758) were analysed. For Tossal de Baltarga, one goat remains, four *Ovis vel Capra*, three cattle, and two pigs were studied. Eight goat remains, 16 cattle, 16 pigs, two horses, seven red deer (*Cervus elaphus*, Linnaeus, 1758), one dog, one badger (*Meles meles*, Linnaeus, 1758), five chickens (*Gallus gallus*, Linnaeus, 1758), and six rabbits came from San Esteve d'Olius. Finally, nine goat remains, 10 cattle, 10 pigs, five horses, five dogs, seven chickens, and three rabbits were selected from Turó de la Rovira.

Only remains that could be reliably identified as different individuals and having a reliable taxonomic determination were selected for this study, considering both laterality and estimated age at death. Exclusively teeth and bones from sub-adult or adult individuals were sampled. The osteological analyses followed the criteria elaborated by Zeder & Pilaar (2010) for teeth and by Boessneck (1969) and Zeder & Lapham (2010) for the post-cranial skeleton to differentiate between goat and sheep. The discrimination between wild boar and domesticated pig was determined by the dimensions of anatomical elements and comparing them to the osteological reference collections from the Institut Català de Paleoeologia Humana i Evolució Social (IPHES-CERCA). Age at death was estimated by observing the epiphyseal fusion of long bones, following the methodologies proposed by Barone (1976), and considering tooth eruption (Hillson 2005) and wear stage, as described by Payne (1973).

Table 3.1 List of sheep elements (bones and teeth) sampled and analysed in this study: sample ID, taxon, provenience site, element, age category, and analysis performed.

Sample	Taxon	Site	Element	Age Category	Analysis performed
MC 11132	<i>Ovis aries</i>	Mas Castellar de Pontós	M ₃	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 11134	<i>Ovis aries</i>		M ₃	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 11138	<i>Ovis aries</i>		M ₃	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 11144	<i>Ovis aries</i>		Metapod + M ₂	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 11146	<i>Ovis aries</i>		Metatarsus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 11159	<i>Ovis aries</i>		Calcaneus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 11216	<i>Ovis aries</i>		Astragalus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 11217	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 12023	<i>Ovis aries</i>		M ₂	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 20102	<i>Ovis aries</i>		M ₂	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 20129	<i>Ovis aries</i>	Tossal de Baltarga	Phalanx I	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 20158	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 20160	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
MC 20165	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
MC 20168	<i>Ovis aries</i>		Humerus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
MC 100031	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
BTB 3249	<i>Ovis aries</i>		Mandible + M ₂	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
BTB 3249.2	<i>Ovis aries</i>		Radius	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
BTB 3249.3	<i>Ovis aries</i>		Radius	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
BTB 3270	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
BTB 3271	<i>Ovis aries</i>	Sant Esteve d'Olius	Mandible + M ₂	Subadult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
BTB 3031	<i>Ovis aries</i>		M ₃	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
O 174	<i>Ovis aries</i>		Mandible + M ₂	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
O 205	<i>Ovis aries</i>		M ₂ + M ₃	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
O 227	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 318	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
O 339	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 348	<i>Ovis aries</i>		Mandible + M ₂	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
O 361	<i>Ovis aries</i>		Humerus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 379	<i>Ovis aries</i>		Humerus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 385	<i>Ovis aries</i>	Turó de la Rovira	Mandible	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 387	<i>Ovis aries</i>		Metacarpus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 397	<i>Ovis aries</i>		Metatarsus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 405	<i>Ovis aries</i>		Mandible	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 438	<i>Ovis aries</i>		Radius	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 452	<i>Ovis aries</i>		Metacarpus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 478	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
O 482	<i>Ovis aries</i>		M ₂	Adult	$\delta^{18}\text{O}+\delta^{13}\text{C}$
O 484	<i>Ovis aries</i>		Mandible + M ₂	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
O 496	<i>Ovis aries</i>		Metatarsus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
O 500	<i>Ovis aries</i>		Radius	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 415.1	<i>Ovis aries</i>		Mandible	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 415.2	<i>Ovis aries</i>		Mandible	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 439	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 465	<i>Ovis aries</i>		Mandible	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 707	<i>Ovis aries</i>		Tibia	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 725	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
TR 763	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$
TR 819	<i>Ovis aries</i>		Radius	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$
TR 831	<i>Ovis aries</i>		Mandible + M ₂ + M ₃	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$; $\delta^{18}\text{O}+\delta^{13}\text{C}$; $^{87}\text{Sr}/^{86}\text{Sr}$
TR 1035	<i>Ovis aries</i>		Metatarsus	Adult	$\delta^{13}\text{C}+\delta^{15}\text{N}$

Table 3.2 List domestic and wild animal bones sampled and analysed in this study: sample ID, provenience site, taxon, element, and age category.

<i>Sample</i>	<i>Site</i>	<i>Taxon</i>	<i>Element</i>	<i>Age Category</i>
MC 11144	Mas Castellar de Pontós	<i>Capra hircus</i>	Mandible	Adult
MC 20160		<i>Capra hircus</i>	Mandible	Adult
MC 20162		<i>Capra hircus</i>	Humerus	Adult
MC 100030		<i>Capra hircus</i>	Tibia	Adult
BTB 3250	Tossal de Baltarga	<i>Capra hircus</i>	Mandible	Subadult
O 181	Sant Esteve d'Olius	<i>Capra hircus</i>	Metacarpus	Adult
O 186		<i>Capra hircus</i>	Mandible	Adult
O 294		<i>Capra hircus</i>	Tibia	Adult
O 297		<i>Capra hircus</i>	Phalanx I	Adult
O 309		<i>Capra hircus</i>	Phalanx I	Adult
O 403		<i>Capra hircus</i>	Phalanx I	Adult
O 423		<i>Capra hircus</i>	Phalanx I	Adult
O 496		<i>Capra hircus</i>	Humerus	Adult
TR 707		<i>Capra hircus</i>	Mandible	Adult
TR 719		<i>Capra hircus</i>	Mandible	Adult
TR 726	Turó de la Rovira	<i>Capra hircus</i>	Phalanx I	Adult
TR 729		<i>Capra hircus</i>	Humerus	Adult
TR 739		<i>Capra hircus</i>	Mandible	Adult
TR 748		<i>Capra hircus</i>	Phalanx I	Adult
TR 805		<i>Capra hircus</i>	Mandible	Adult
TR 821		<i>Capra hircus</i>	Phalanx I	Adult
TR 10004		<i>Capra hircus</i>	Astragalus	Adult
BTB 3051	Tossal de Baltarga	<i>Ovis vel Capra</i>	Humerus	Adult
BTB 3073		<i>Ovis vel Capra</i>	Tibia	Adult
BTB 3099		<i>Ovis vel Capra</i>	Tibia	Adult
BTB 3159		<i>Ovis vel Capra</i>	Ulna	Adult
MC 11125	Mas Castellar de Pontós	<i>Bos taurus</i>	Mandible	Adult
MC 11145		<i>Bos taurus</i>	Metacarpus	Adult
MC 11150		<i>Bos taurus</i>	Mandible	Adult
MC 20162		<i>Bos taurus</i>	Tibia	Adult
MC 20168	Tossal de Baltarga	<i>Bos taurus</i>	Radius	Adult
MC 100030		<i>Bos taurus</i>	Phalanx I	Adult
BTB 3031		<i>Bos taurus</i>	Mandible	Adult
BTB 3051		<i>Bos taurus</i>	Mandible	Adult
BTB 3064		<i>Bos taurus</i>	Phalanx II	Adult
O 142		<i>Bos taurus</i>	Tibia	Adult
O 181		<i>Bos taurus</i>	Tibia	Adult
O 195		<i>Bos taurus</i>	Metacarpus	Adult
O 205		<i>Bos taurus</i>	Radius	Adult
O 318		<i>Bos taurus</i>	Humerus	Adult
O 320	Sant Esteve d'Olius	<i>Bos taurus</i>	Humerus	Adult
O 329		<i>Bos taurus</i>	Radius	Adult
O 349		<i>Bos taurus</i>	Ulna	Adult
O 381		<i>Bos taurus</i>	Tibia	Adult
O 387		<i>Bos taurus</i>	Tibia	Adult
O 394		<i>Bos taurus</i>	Tibia	Adult
O 397		<i>Bos taurus</i>	Metatarsus	Adult
O 399		<i>Bos taurus</i>	Radius	Adult
O 423		<i>Bos taurus</i>	Humerus	Adult
O 448		<i>Bos taurus</i>	Humerus	Adult
O 482		<i>Bos taurus</i>	Metatarsus	Adult

<i>Sample</i>	<i>Site</i>	<i>Taxon</i>	<i>Element</i>	<i>Age Category</i>
TR 412	Turó de la Rovira	<i>Bos taurus</i>	Femur	Adult
TR 415		<i>Bos taurus</i>	Phalanx I	Adult
TR 439		<i>Bos taurus</i>	Metatarsus	Adult
TR 707		<i>Bos taurus</i>	Metacarpus	Adult
TR 715		<i>Bos taurus</i>	Metatarsus	Adult
TR 719		<i>Bos taurus</i>	Mandible	Adult
TR 725		<i>Bos taurus</i>	Ulna	Adult
TR 729		<i>Bos taurus</i>	Tibia	Adult
TR 739		<i>Bos taurus</i>	Tibia	Adult
TR 1035		<i>Bos taurus</i>	Metacarpus	Adult
MC 11218	Mas Castellar de Pontós	<i>Sus domesticus</i>	Cranium	Adult
MC 20158		<i>Sus domesticus</i>	Mandible	Adult
MC 20168		<i>Sus domesticus</i>	Mandible	Adult
MC 100033	Tossal de Baltarga	<i>Sus domesticus</i>	Ulna	Adult
BTB 3029		<i>Sus domesticus</i>	Mandible	Adult
BTB 3051		<i>Sus domesticus</i>	Mandible	Adult
O 186	Sant Esteve d'Olius	<i>Sus domesticus</i>	Mandible	Adult
O 205		<i>Sus domesticus</i>	Mandible	Adult
O 235		<i>Sus domesticus</i>	Radius	Adult
O 245		<i>Sus domesticus</i>	Mandible	Adult
O 309		<i>Sus domesticus</i>	Tibia	Adult
O 311		<i>Sus domesticus</i>	Mandible	Adult
O 318		<i>Sus domesticus</i>	Tibia	Adult
O 329		<i>Sus domesticus</i>	Maxilla	Adult
O 371		<i>Sus domesticus</i>	Calcaneus	Adult
O 385.1		<i>Sus domesticus</i>	Mandible	Adult
O 385.2		<i>Sus domesticus</i>	Mandible	Subadult
O 397		<i>Sus domesticus</i>	Mandible	Adult
O 399		<i>Sus domesticus</i>	Maxilla	Adult
O 427		<i>Sus domesticus</i>	Calcaneus	Adult
O 482		<i>Sus domesticus</i>	Mandible	Adult
O 486		<i>Sus domesticus</i>	Ulna	Adult
TR 415	Turó de la Rovira	<i>Sus domesticus</i>	Humerus	Adult
TR 465		<i>Sus domesticus</i>	Metapod	Adult
TR 707		<i>Sus domesticus</i>	Humerus	Adult
TR 725		<i>Sus domesticus</i>	Mandible	Adult
TR 739		<i>Sus domesticus</i>	Mandible	Adult
TR 748		<i>Sus domesticus</i>	Metapod	Adult
TR 765		<i>Sus domesticus</i>	Metapod	Adult
TR 766		<i>Sus domesticus</i>	Scapula	Adult
TR 821		<i>Sus domesticus</i>	Metapod	Adult
TR 1065		<i>Sus domesticus</i>	Metapod	Adult
MC 11123	Mas Castellar de Pontós	<i>Equus caballus</i>	Metatarsus	Adult
MC 11159		<i>Equus caballus</i>	Phalanx I	Adult
MC 20160		<i>Equus caballus</i>	Phalanx II	Adult
MC 20165	Sant Esteve d'Olius	<i>Equus caballus</i>	Tibia	Adult
MC 20168		<i>Equus caballus</i>	Humerus	Adult
O 148		<i>Equus caballus</i>	Scapula	Adult
O 397	Turó de la Rovira	<i>Equus caballus</i>	Mandible	Adult
TR 415		<i>Equus caballus</i>	Mandible	Adult
TR 439		<i>Equus caballus</i>	Pelvis	Adult

<i>Sample</i>	<i>Site</i>	<i>Taxon</i>	<i>Element</i>	<i>Age Category</i>
TR 729	Turó de la Rovira	<i>Equus caballus</i>	Humerus	Adult
TR 805		<i>Equus caballus</i>	Femur	Adult
TR 1037		<i>Equus caballus</i>	Mandible	Adult
O 205	Sant Esteve d'Olius	<i>Cervus elaphus</i>	Phalanx I	Adult
O 245		<i>Cervus elaphus</i>	Tibia	Adult
O 309		<i>Cervus elaphus</i>	Metatarsus	Adult
O 339		<i>Cervus elaphus</i>	Metatarsus	Adult
O 387		<i>Cervus elaphus</i>	Radius	Adult
O 421		<i>Cervus elaphus</i>	Phalanx I	Adult
O 452		<i>Cervus elaphus</i>	Phalanx I	Adult
MC 12028.1	Mas Castellar de Pontós	<i>Canis familiaris</i>	Humerus	Adult
MC 12028.2		<i>Canis familiaris</i>	Humerus	Adult
MC 12028.3		<i>Canis familiaris</i>	Ulna	Adult
MC 20165		<i>Canis familiaris</i>	Mandible	Adult
MC 100031		<i>Canis familiaris</i>	Metacarpus	Adult
O 349	Sant Esteve d'Olius	<i>Canis familiaris</i>	Ulna	Adult
TR 415		<i>Canis familiaris</i>	Radius	Adult
TR 719	Turó de la Rovira	<i>Canis familiaris</i>	Metapod	Adult
TR 726		<i>Canis familiaris</i>	Pelvis	Adult
TR 766		<i>Canis familiaris</i>	Metapod	Adult
TR 819		<i>Canis familiaris</i>	Metapod	Adult
O 257		<i>Meles meles</i>	Tibia	Adult
MC 11221	Mas Castellar de Pontós	<i>Milvus milvus</i>	Humerus	Adult
MC 11145		Bird	Ulna	Adult
MC 20158		Bird	Radius	Adult
O 186.1	Sant Esteve d'Olius	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult
O 186.2		<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult
O 205		<i>Gallus gallus</i>	Tibia-Tarsus	Adult
O 361		<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult
O 387		<i>Gallus gallus</i>	Tibia-Tarsus	Adult
TR 528.1		<i>Gallus gallus</i>	Humerus	Adult
TR 528.2		<i>Gallus gallus</i>	Humerus	Adult
TR 719	Turó de la Rovira	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult
TR 763		<i>Gallus gallus</i>	Femur	Adult
TR 764.1		<i>Gallus gallus</i>	Tibia-Tarsus	Adult
TR 764.2		<i>Gallus gallus</i>	Tibia-Tarsus	Adult
TR 765		<i>Gallus gallus</i>	Tibia-Tarsus	Adult
MC 20122	Mas Castellar de Pontós	<i>Oryctolagus cuniculus</i>	Humerus	Adult
MC 20158		<i>Oryctolagus cuniculus</i>	Pelvis	Adult
MC 20160		<i>Oryctolagus cuniculus</i>	Radius	Adult
MC 20162		<i>Oryctolagus cuniculus</i>	Radius	Adult
MC 20165.1		<i>Oryctolagus cuniculus</i>	Ulna	Adult
MC 20165.2		<i>Oryctolagus cuniculus</i>	Ulna	Adult
O 381		<i>Oryctolagus cuniculus</i>	Tibia	Adult
O 397	Sant Esteve d'Olius	<i>Oryctolagus cuniculus</i>	Tibia	Adult
O 459		<i>Oryctolagus cuniculus</i>	Tibia	Adult
O 486.1		<i>Oryctolagus cuniculus</i>	Tibia	Adult
O 486.2		<i>Oryctolagus cuniculus</i>	Tibia	Adult
TR 439	Turó de la Rovira	<i>Oryctolagus cuniculus</i>	Pelvis	Subadult
TR 463		<i>Oryctolagus cuniculus</i>	Humerus	Adult
TR 739		<i>Oryctolagus cuniculus</i>	Metapod	Adult

3.3 Sequential $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotope analyses

After cleaning the surface of the selected teeth by abrasion with a tungsten drill, enamel bands were sequentially sampled using a diamond bit. Sampling was performed on the buccal surface, on the distal lobe of M_2 and the central lobe of M_3 (Figure 3.2). The samples were progressively taken at 1-2 mm intervals along the whole crown height, from the apex to the enamel root junction (ERJ; Figure 3.3).

Pre-treated samples weighting $\sim 600\ \mu\text{g}$ were measured using an automated carbonate preparation device (KIEL-III) interfaced to a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Department of Geosciences), University of Arizona (USA), with scientific supervision from Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C . To ensure accuracy and precision, measurements were checked



Figure 3.2 Sequential sampling of the second and third right lower sheep molars from Mas Castellar de Pontós (MC 20165).

The positions of the samples-bands were recorded in mm starting from the ERJ.

A total of 473 powdered enamel samples (weighing between 2.5 and 13.7 mg) were drilled and chemically treated at the Biomolecular Laboratory of the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), following the protocol described in Balasse *et al.* (2002) and modified by Tornero *et al.* (2013). To eliminate contamination from exogenous carbonates, samples underwent pre-treatment in 0.1 M acetic acid [CH_3COOH] (0.1 ml solution/mg of sample) for four hours, rinsed five times in distilled water and dried in an oven at 70°C for 48 hours (Figure 3.4).



Figure 3.3 Sampling for the sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (photo by Ana Fagoaga Moreno).

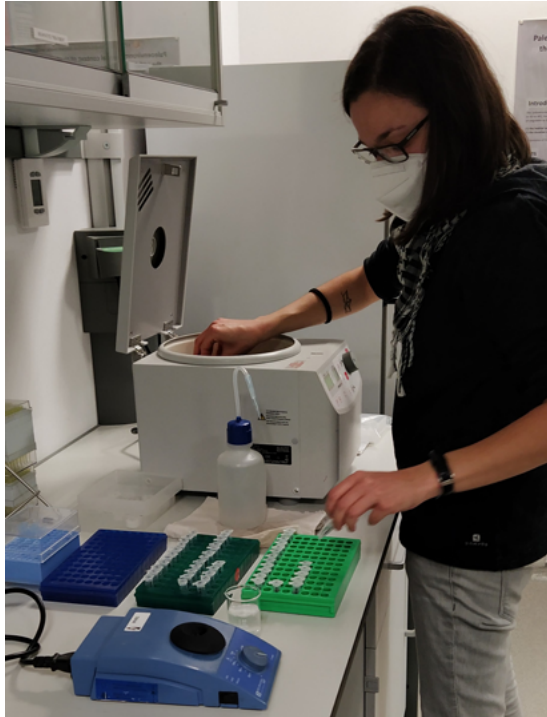


Figure 3.4 Chemical pre-treatment for the sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (photo by Sandra Bañuls Cardona).

and calibrated using NBS-19 and NBS-18 international standards. The mean analytical precision within each run and from replicate measurements of standards during analysis was $\pm 0.10\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.08\text{‰}$ for $\delta^{13}\text{C}$ (1σ). Isotope composition is reported in δ notation and expressed per mil (‰), stating the deviation of the isotope ratio from the V-PDB (Vienna-Pee Dee Belemnite) standard for both carbon and oxygen values (McKinney *et al.* 1950; Gross 2017).

3.4 $^{87}\text{Sr}/^{86}\text{Sr}$ isotope analysis

Strontium isotope analysis was performed on 12 teeth from seven individuals. Samples were collected from three individuals whose molars exhibit altitudinal mobility based on the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (BTB 3270, O 205, and TR 831), as well as from four sedentary individuals (MC 20160, O 174, O 484, and TR 725). Sampling for strontium isotope analysis was performed close to the

point of maximum and minimum events recorded in the oxygen series. This sampling strategy was carried out to assess the compatibility and effectiveness of combining this method with the sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values.

Enamel samples, weighing over 10 mg, were processed at the British Geological Survey - BGS (UK), with technical support from Doris Wagner. Following the cleaning of each tooth surface with a tungsten carbide dental bur, an enamel sample was cut using a flexible diamond-edged rotary dental saw. Sampling was conducted on the buccal side, specifically on the anterior lobe of M_2 and M_3 , except for two cases (TR M2 831, TR M2 725) on the distal lobe of M_2 , on the lingual surface and in one instance (TR M3 725) on the central lobe of M_3 , on the lingual side. A minimum of one and a maximum of three samples per tooth were cut. All sample surfaces underwent mechanical cleaning with a diamond bur to remove adhering dentine. The resulting sample was transferred to a clean (class 100, laminar flow) working area for further preparation. Initially, the sample underwent ultrasonic cleaning in high-purity water to remove dust, followed by two rinses. It was then soaked for an hour at 60°C , rinsed twice, and dried before being weighed into pre-cleaned Teflon beakers. The sample was mixed with ^{84}Sr tracer solution, dissolved in Teflon distilled 8M HNO_3 and converted to chloride form using 6M HCl . Strontium was collected using Eichrom AG50 X8 resin columns (Figure 3.5). Strontium was loaded onto a single Re Filament following the method of Birck (1986) and the isotope composition and strontium concentrations were determined by Thermal Ionisation Mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer (Figure 3.6). The international standard for $^{87}\text{Sr}/^{86}\text{Sr}$, NBS987, yielded a value of

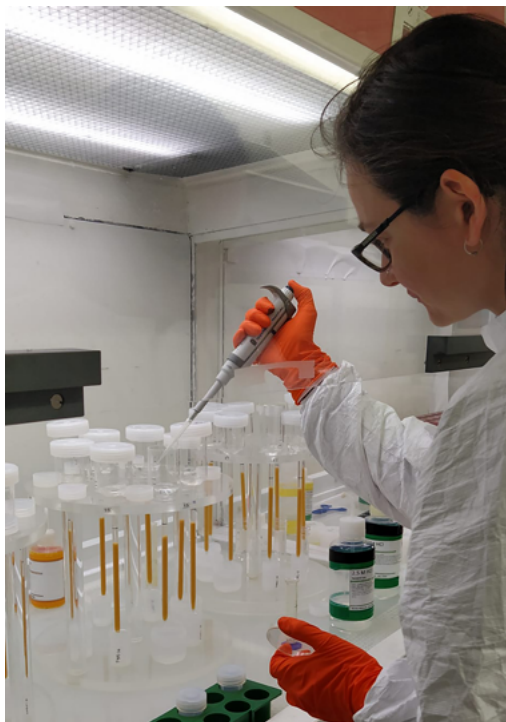


Figure 3.5 Strontium collection process using resin columns (photo by Doris Wagner).

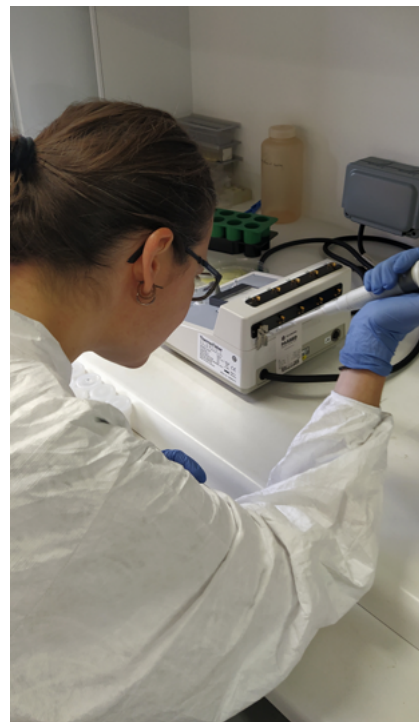


Figure 3.6 Sample loaded onto an outgassed filament ribbon using a pipette (photo by Doris Wagner).

$0.710258 \pm .000020$ (2SD, $n=8$) during the analysis of these samples. This is within uncertainty of the accepted value of 0.710250 and hence the data are uncorrected relative to the standard.

3.5 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ bulk analysis

Sample preparation and collagen extraction were conducted at the Biomarkers Laboratory of the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA). A small bone fragment was cut and removed from each specimen using a Dremel diamond rotating wheel (Figure 3.7a,b). Subsequently, the bone shards' surface was cleaned by abrasion with a tungsten drill to remove any visible contaminants. The collagen extraction was carried out following the protocol proposed by Longin (1971) and modified by Bocherens *et al.* (1991). The bone fragments were initially soaked in 0.5 M HCl for demineralisation, rinsed several times with distilled water, and

soaked in NaOH (0.125 M) for 20 hours to remove potential organic contaminants (Figure 3.8 and Figure 3.9). After another round of rinsing, the samples were diluted and gelatinised with 0.01 M HCl at 100°C for 17 hours (pH 2). Finally, the collagen samples were microfiltered using 5 μm filters



Figure 3.7 Sampling of a bone fragment to analyse $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (frame from a video; Figure 3.7a); right radio-ulna of pig from Sant Esteve d'Olius sampled for analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (O 235; Figure 3.7b).

to eliminate any residues before being frozen. The samples were lyophilised and measured at the Institut de Ciència i Tecnologia Ambientals (ICTA-UAB; Figure 3.10). Gelatin-collagen



Figure 3.8 Bone fragments soaked in 0.5 M HCl for demineralisation (photoby Maria Dolors Guillén Espínola).

samples weighing about 300 μ m were set into tin capsules and analysed using a Thermo Flash 1112 elemental analyser (EA) coupled to a Thermo Delta V Advantage isotope ratio mass spectrometer (IRMS) with a ConFlo III interface (Figure 3.11).

The mean analytical precision was assessed using the international standard laboratory IAEA 600 (caffeine; theoretical values: $\delta^{13}\text{C} = -27.77 \pm 0.04\text{‰}$, $\delta^{15}\text{N} = +1.0 \pm 0.2\text{‰}$) and used for data calibration. The average analytical error was $<0.05\text{‰}$ (1σ) for $\delta^{13}\text{C}$ and $\pm 0.13\text{‰}$ $\delta^{15}\text{N}$, determined within each run and from repeated measurements of the standard.

The isotope ratios are reported for carbon as $\delta^{13}\text{C}$ Vienna Pee Dee

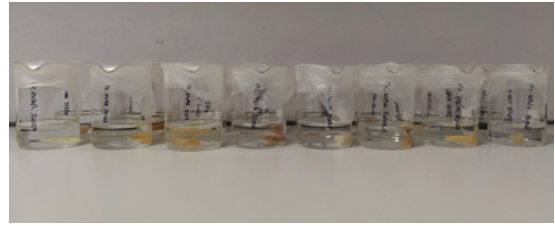


Figure 3.9 Bone fragments soaked in 0.25 M NaOH for 20 hours to remove organic contaminants.

Belemnite (V-PDB) and for nitrogen as $\delta^{15}\text{N}$ atmospheric nitrogen (AIR): $\chi = \frac{1}{4} (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000\text{‰}$, where χ stands for ^{13}C or ^{15}N and R stands for $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$. To evaluate the reliability of the collagen extracts' isotopic signature, several quality criteria were applied: a yield of extraction $\geq 10 \text{ mg}\cdot\text{g}^{-1}$, percentages

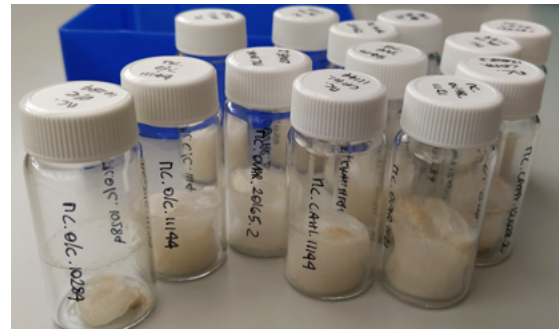


Figure 3.10 Lyophilised samples from Mas Castellar de Pontós.

of C $\geq 30\%$ and N $\geq 10\%$, and a range of atomic C:N ratio between 2.9 and 3.6 (DeNiro 1985; Ambrose 1990; Van Klinken 1999).



Figure 3.11 Samples in the tin capsule during weighing in the microbalance.

3.6 Statistical analyses

The free software Past v.4.03 (Hammer *et al.*, 2001) was employed for the statistical analyses of the isotopic data. The ANOVA and Kruskal-Wallis tests were used to test the statistical significance among groups of isotopic values, setting the significance p-value at <0.05.



Results

4

4.1 Reproduction patterns

This section presents the results related to the first of the three research objectives of this thesis: the sheep reproduction strategies adopted by Iberian communities in the north-eastern Iberian Peninsula during the Middle/Late Iron Age.

The first article of this PhD thesis, titled “An insight of sheep’s seasonal reproductive patterns on the northeastern Iberian Peninsula before the Roman influence: The Case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain)”, presents the results of a preliminary test focused on a portion of the sheep dental remains from Mas Castellar de Pontós. This site was selected as a pilot study due to the abundance of multidisciplinary data available, the excellent state of preservation of faunal remains and the large number of remains available to perform the analyses.

The second article in this section, titled “Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian

Peninsula (3rd c. BC)”, outlines the results on the season and seasonality of sheep births and the duration of the lambing period in all four settlements studied.

4.1.1 Paper 1a. An insight of sheep’s seasonal reproductive patterns on the northeastern Iberian Peninsula before the Roman influence: The case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain)

This article presents the study on the seasonal reproduction strategies of sheep adopted by herders in the Mas Castellar de Pontós rural settlement. The data obtained provide pioneering insights into this topic within the context of the north-eastern Iberian Peninsula during the Middle/Late Iron Age. The sequential analyses of $\delta^{18}\text{O}$ isotope values performed on dental enamel provide evidence of diverse sheep reproductive patterns and different demographic management strategies within the settlement. Indeed, both natural (late winter/spring) and ‘out-of-season’ (autumn) births are attested. Furthermore, autumn births

occurred within a restricted timeframe. This pronounced anthropogenic manipulation of the reproduction cycles suggests a very complex and well-planned organisation of sheep husbandry within the rural settlement, related to the type of exploitation required and the environmental conditions of the area.

This preliminary study enabled the investigation of a subject that had not been addressed by traditional studies, revealing the advanced zootechnical knowledge of the Iron Age Iberian communities. Moreover, the results highlight the enormous potential of biogeochemical analyses in uncovering valuable insights into Protohistoric chronologies in the Iberian Peninsula. Finally, this research has provided the starting point for the development of this doctoral thesis.

An insight of sheep's seasonal reproductive patterns on the northeastern Iberian Peninsula before the Roman influence: The Case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain).

Messana, Chiara^{1&2}; Tornero, Carlos^{3&1}; Colominas, Lúdia⁴; Pons, Enriqueta⁵

¹ Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain;

² Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain;

³ Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193 Bellaterra, Spain

⁴ Institut Català d'Arqueologia Clàssica (ICAC-CERCA), Plaça d'en Rovellat s/n, 43003 Tarragona, Spain;

⁵ MAC-Girona, Pedret, 95, 17007 Girona, Spain

This study was carried out in the framework of a wider research project focused on the analysis of the Late Iron Age livestock strategies in the north-eastern Iberian Peninsula, just before the arrival of the Roman influence. To characterise seasonal breeding strategies, here are presented the preliminary results of the sequential analyses performed on sheep's tooth enamel from the rural settlement of Mas Castellar de Pontós.

Mas Castellar de Pontós is located on the Empordà plain (Girona, highest altitude: 140-160 m. a.s.l.), approximately 17 km equidistant from the Greek colonies of Rhode and Emporion. The rural establishment was occupied between 250-180 BC and it was a specialised agricultural settlement located on a natural path of communication between the coast and the inland areas. There, husbandry (mainly focused on caprines with the sheep predominance) was practised to obtain diversified products for self-sufficiency.

Sheep reproduction patterns are investigated here through the stable isotope analyses in order to characterise birth seasonality and the duration of the lambing period. Moreover, evidence of sheep lambing de-seasoning is searched, to obtain a more general picture of sheep demographic management and the complexity of the animal husbandry organisation of the Late Iron Age societies.

Results show evidence of the existence of diversified sheep reproductive patterns and, consequently, different demographic management deployed within the rural establishment. Indeed, both natural (late winter-spring) and "out-of-season" (autumn) births are attested. Therefore, these data suggest that the sheep husbandry organisation adopted by the last Iron Age societies was much more complex and planned than previously glimpsed by studies to date.

Keywords: Stable oxygen isotope, seasonal reproductive patterns, livestock strategies, Late Iron Age, NE Iberian Peninsula

1. Introduction

1.1 Historical background and research purpose

Before the Roman conquest, the Late Iron Age Iberian societies were characterised by a hierarchical structure, organised into different centralised political entities. A whole range of interconnected settlements, including fortified settlements, rural establishments, small villages, and silos fields, emerged (Sanmartí i Grego 2014; Sanmartí i Grego 2021; Nieto Espinet *et al.* 2021). They all had specific functions and were structured around central nucleus, the so-called first-order cities; the main function of the latter was the control and centralisation of agricultural production (Asensio *et al.* 1998; Bouso *et al.* 2000; Sanmartí i Grego 2004; Sanmartí i Grego 2014; Sanmartí i Grego *et al.* 2019; Nieto Espinet *et al.* 2021). Indeed, the economic strategies developed by these human groups showed a predominantly local agricultural economy, strongly related to the ecological conditions of each area and focused on self-sufficiency, with cereal surplus as the main exchange product (Asensio *et al.* 2003; Asensio 2013; Prats *et al.* 2020). In the framework of this economy, animal husbandry was a central activity, mainly focused on caprines, with the sheep predominance. The zooarchaeological studies carried out so far have proven the adoption of diversified livestock strategies mainly oriented toward self-sufficiency and adapted to the necessities of each settlement (Albizuri & Nadal 1999; Franquesa *et al.* 2000, Colominas 2008; Colominas 2013; Colominas *et al.* 2019). In order to obtain an accurate and complete insight into the different livestock strategies displayed in the north-eastern Iberian Peninsula during the Late Iron Age, the application of biogeochemical analyses

(stable isotopes) becomes necessary. The contribution of isotopic analysis has proven to be a fundamental tool for complementing and enriching traditional zooarchaeological studies in the reconstruction of husbandry strategies in the past. Nevertheless, biogeochemical data are still very scarce for protohistoric periods in the Iberian Peninsula. To begin to fill this lack of data, the present study investigates the seasonal reproductive strategies employed in the rural establishment of Mas Castellar de Pontós, occupied during the Late Iron Age and located in the northeast of the Iberian Peninsula.

1.2 Sequential oxygen isotope analysis to infer seasonal reproductive patterns

Sequential stable isotope analyses performed on the sheep molars enamel provide innovative life-history data about past herds (Balasse 2002). Once fully mineralised, tooth enamel does not turn over and reflects the isotopic signal recorded during the tooth formation. The oxygen isotopic composition measured in the enamel mineral fraction (bioapatite) directly derived from ingested water and plants consumption (Longinelli 1984; Luz *et al.* 1984). These are related to the meteoric water and oxygen values vary according to the seasonal changes. At mid and high latitudes, the warmest season is reflected in higher $\delta^{18}\text{O}$ values, whereas the coldest one in lower $\delta^{18}\text{O}$ values (Gat 1980). Seasonality and reproductive dynamics of sampled specimens are investigated on the basis of the $\delta^{18}\text{O}$ sequences recorded in each tooth crown.

2. Mas Castellar de Pontós

2.1 The site

Mas Castellar de Pontós is located on the Empordà plain (Girona, highest

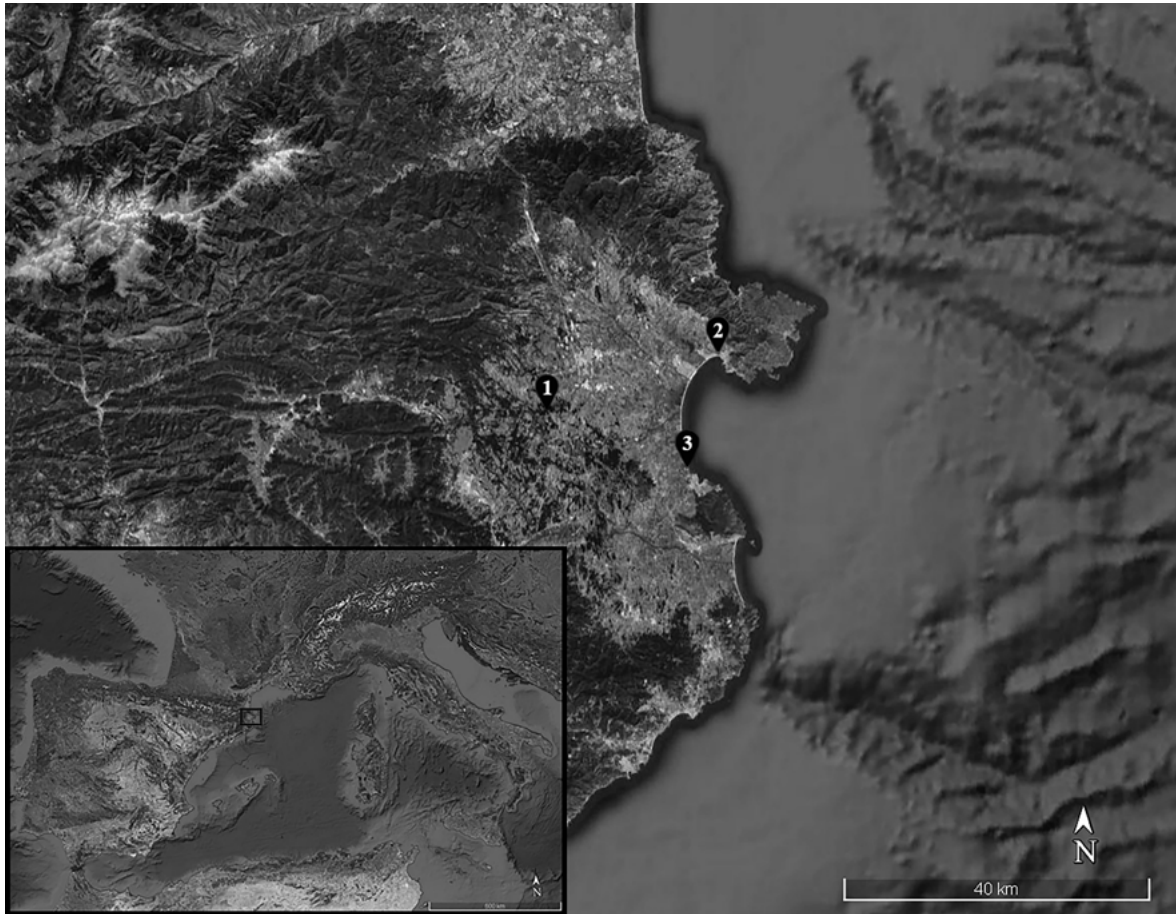


Figure 4.1. Location of Mas Castellar de Pontós site (1) and the Greek colonies of Rhode (2) and Emporion (3) (Google Earth Pro modified).

altitude: 140-160 m. a.s.l.; Figure 4.1), in an interfluvial position between a tributary of the Muga River to the north and the Fluvià River to the south, approximately 17 km equidistant from the Greek colonies of *Rhode* and *Emporion*. This favourable position allowed the site to be a natural way of communication between the coast and inland. Furthermore, climatic factors (humidity and mild temperatures) enabled the settlement to become an important economic centre for cereal production, throughout the Iron Age (Pons *et al.* 2010).

The site is located on a promontory and covers an area of approximately 5 ha. The archaeological complex extends across two plains: an upper one called 'Camp de Dalt' and a lower one called 'Camp de Baix'. Human

occupation of Mas Castellar covers a wide chronological frame, divided into six periods, between the end of the seventh century until the beginning of the second century BC (Pons *et al.* 2010; Adroher & Pons 2002).

2.2 The rural establishment

The so-called rural establishment (Figure 4.2), a specialised agricultural settlement, belongs to the fifth period of the site's occupation, that took place between 250-180 BC. It is located on the east side of the 'Camp de Dalt' and was organised along a main axis, from which different domestic units were found. To date, three buildings with complex architecture (houses 1, 2 and 3) and two buildings related to domestic and family use (house 8 and house 10) have been identified (Colominas 2008; Pons *et al.* 2010). Associated with

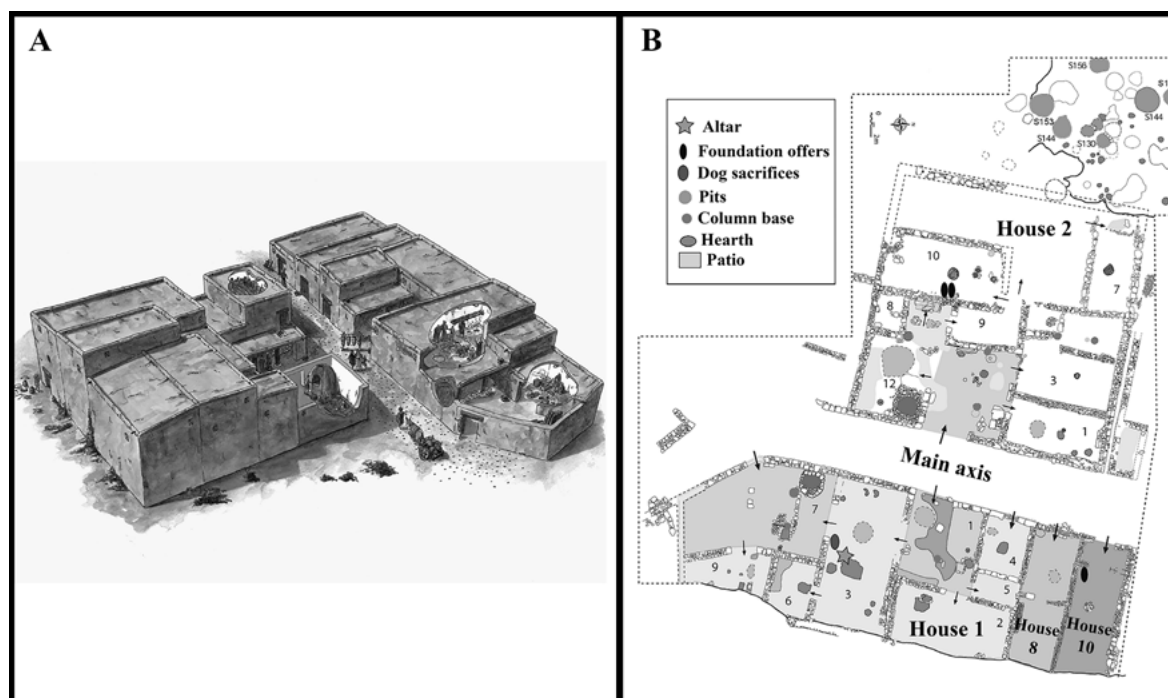


Figure 4.2. A. Reproduction (author Sergi Segura 2021) and plan (author C. Garcia-Dalmau 2010, modified) of the rural settlement (Phase V, between 250-180 BC). B. The teeth selected for this study come from silos 130 and 153 and House 2.

the rural establishment, located in the north-western area, was an extensive silos field (Zone 20) (Pons *et al.* 2010).

Managed by a rural aristocracy, the rural establishment was an important commercial enclave for cereal production and a major reserve centre for the entire Emporion area (Bouso *et al.* 2000; Fuertes *et al.* 2002). Husbandry mainly focused on caprines, where sheep domain and was focused to obtain diversified products for self-sufficiency (Bouso *et al.* 2000; Colominas 2008; Colominas 2013).

3. Material and Methods

3.1 Material

Eight lower molars (five second molars and three third molars) of eight sheep (*Ovis aries*) were selected and analysed for this study (Table 4.1). Two of the second molars were extracted from mandibles, while all the others were isolated teeth. Only molars with a

completely formed crown and early wear stage were selected. Three of the second molars belong to the Payne's (1973) age class E (2-3 years) and two to the class F (3-4 years), while three third molars belong to the class G (4-6 years).

Five teeth were found in House 2 of the rural establishment, while three second molars were discovered inside two pits (silos 153 and 130) associated with the house.

3.2 Methods

The surface of the selected teeth has been cleaned by abrasion with a tungsten drill bit. Afterwards, enamel bands were sequentially sampled using a diamond bit. Sampling was performed on the buccal side, on the posterior lobe of M_2 and on the middle lobe of M_3 . All the samples were taken at 1-2 mm intervals along the whole crown height, starting from the crown and their positions from the enamel-root junction (ERJ) were recorded.

Table 4.1. Results from the calculation of the best fit (by method of least squares) for combined variation of X (period), A (amplitude), x_0 (delay) and M (mean). The Pearson's correlation coefficient (R) is also indicated.

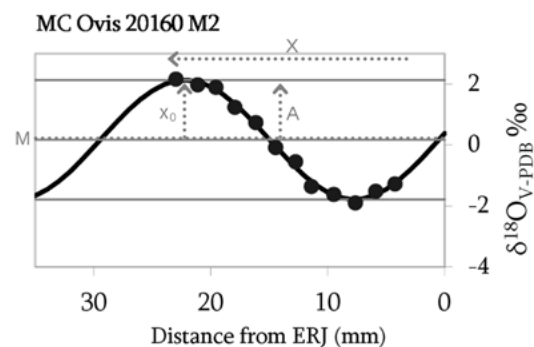
Sheep ID	Provenance	Tooth	Side	Wear stage	Age estimation
MC Ovis 20160	Pit 153	M ₂	Right	E	2-3 years
MC Ovis 20165	Pit 153	M ₂	Right	F	3-4 years
MC Ovis 20102	Pit 130	M ₂	Left	E	2-3 years
MC Ovis 12023	House 2, room 12	M ₂	Left	E	2-3 years
MC Ovis 11144	House 2, room 10a	M ₂	Left	F	2-6 years
MC Ovis 11132	House 2, room 7a	M ₃	Right	G	4-6 years
MC Ovis 11134	House 2, room 6a	M ₃	Left	G	4-6 years
MC Ovis 11138	House 2, room 9	M ₃	Left	G	4-6 years

Teeth wear stages after Payne 1973

A total number of 120 samples were drilled. Between 13 and 19 samples were sampled per tooth. Powdered enamel samples (weighing between 3.8 and 13.7 mg) were chemically pre-treated at the Biomolecular Laboratory of the Institut Català de Paleoeologia Humana i Evolució Social (IPHES-CERCA), following the protocol described in Balasse *et al.* (2002) and modified by Tornero *et al.* (2013). Samples were treated to remove exogenous carbonates (4h in 0.1 M acetic acid; 0.1 ml solution/mg of sample), rinsed in distilled water several times and dried in an oven at 70°C for 48h.

Once treated, samples were analysed using a KIEL-III device coupled to a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Dept. of Geosciences), University of Arizona (USA), with scientific supervision from Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. The isotope ratio measurement is calibrated based on repeated measurements of NBS-19 and NBS-18. The mean analytical precision within each run varies from 0.04‰ to 0.05‰. Results are expressed in δ and ‰, in agreement with the corrections from standard V-PDB (Vienna-Pee Dee Belemnite) oxygen values.

Finally, seasonal reproduction patterns were assessed following Balasse *et al.* 2003, 2012, and Tornero *et al.* 2013. In order to quantify the inter-individual variability in tooth size and to define the position of the maximum $\delta^{18}\text{O}$ value in the tooth crown (x_0/X), the $\delta^{18}\text{O}$ sequences were modelled using the equation described by Balasse *et al.* 2012, based on a cosine function. The model includes four parameters: the period of the cycle (X), expressed in mm and corresponding to the length of tooth crown potentially formed over a year; the amplitude of the isotopic signal (A), expressed in ‰; the delay (x_0) expressed in mm, corresponding to the position in tooth crown where the $\delta^{18}\text{O}$ has his maximum value; and the mean (M), expressed in ‰ (Figure 4.3).

**Figure 4.3.** Description of the four parameters defined in the modelling procedure (Balasse *et al.* 2012). The model is applied to the sequence of $\delta^{18}\text{O}$ values of one of the molars under study. X = period, x_0 = delay, M = mean, A = amplitude.

As the inter-variability in (x_0/X) reflects the variability in the birth season, this latter is estimated by comparison with data from modern sheep populations with the known date of birth. These reference data included individuals from Blaise & Balasse 2011, Balasse *et al.* 2012, Balasse *et al.* 2017, Tornero *et al.* 2018, and Balasse *et al.* 2020.

4. Results

4.1 Oxygen isotope ratios

Results of the intra-tooth sequences of $\delta^{18}\text{O}$ values are summarised in *Table 4.2* and fully presented in *Table 4.3*. The mean $\delta^{18}\text{O}$ value from all samples is $0.3 \pm 1.2\text{‰}$, ranging from 2.6‰ to -2.3‰ . The mean $\delta^{18}\text{O}$ value within each specimen varies from 1.6‰ to -0.6‰ , maximum values range from 2.6‰ to 1‰ , and minimum values range from 1‰ to -2.3‰ .

Table 4.2. Summarized isotopic results ($\delta^{18}\text{O}$ values) in bioapatite samples from archaeological lower second (M_2) and third (M_3) sheep molars.

Individuals	Sample n°	$\delta^{18}\text{O}_{\text{V-PDB}\text{‰}}$			
		Mean	Range	Max.	Min.
MC Ovis M2 20160	13	0	4.1	2.2	-1.9
MC Ovis M2 20165	14	1	3.2	2.6	-0.6
MC Ovis M2 20102	14	1.6	1.1	2.1	1
MC Ovis M2 12023	19	-0.6	3.9	1.6	-2.3
MC Ovis M2 11144	16	0.2	2.8	1.8	-1.0
MC Ovis M3 11132	14	0.1	1.8	1	-0.8
MC Ovis M3 11134	13	-0.1	2.8	1.2	-1.5
MC Ovis M3 11138	17	0.2	2.7	1.4	-1.3

4.2 Sequential $\delta^{18}\text{O}$ series

Intra-tooth sequences of $\delta^{18}\text{O}$ values on the second and the third molars are shown in *Figure 4.4*. In all specimens, except the Individual 20102's second molar, oxygen sequences show high intra-tooth variation, with a sinusoidal pattern and clear maximum and minimum events that reflect the seasonal cycle. The highest $\delta^{18}\text{O}$ values were recorded during summer, while

the lowest ones during the winter. Season of birth was assessed from $\delta^{18}\text{O}$ sequential series observed in all the molars investigated, identifying the position of the maximum $\delta^{18}\text{O}$ values in the tooth crown and comparing these with modern reference data.

All second and third molars could be modelled and results are shown in *Table 4.4* and *Figure 4.5*, through a circular graph, to visually reflect a complete annual cycle (Balasse *et al.* 2020). The (x_0/X) ratio varies between 0.15 and 0.83 indicating a wide distribution of births over the annual cycle. Indeed, the results suggest that during the Late Iron Age phase, in the rural establishment lambing occurred from the autumn to the late spring. For sheep born in autumn (MC 20160, MC 20165, MC 20102), the duration of lambing period can be estimated to almost two months (0.13 year or 1.5 months); while for sheep born in

spring (M 12023, MC 11144, MC 11132, MC 11134, MC 11138), the duration of lambing period can be estimated to three months considering both M_2 (0.25 year or 3.02 months) and M_3 (0.24 year or 2.90 months).

Table 4.3. $\delta^{18}\text{O}$ values in enamel bioapatite samples from Mas Castellar de Pontós sheep lower second (M_2) and third molars (M_3).

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
MC Ovis	30.84	-0.89	MC Ovis	33.25	1.57	MC Ovis	26.86	2.10	MC Ovis	22.98	2.16
M2 11144	29.09	-1.05	M2 12023	31.76	0.88	M2 20102	25.08	1.92	M2 20160	21.1	1.98
	27.28	-1.04		30	0.59		23.44	1.89		20	1.90
	25.57	-1.00		28.67	-0.19		21.93	1.87		17.93	1.25
	24.02	-0.62		27.18	-0.51		20.23	1.70		16.15	0.74
	22.02	-0.22		24.91	-1.14		18.83	1.79		14.46	-0.08
	20.38	0.24		23.41	-1.52		16.83	1.63		12.75	-0.54
	18.44	0.57		21.62	-1.88		14.63	1.56		11.39	-1.35
	16.86	1.00		20.12	-1.85		13	1.08		9.47	-1.62
	15.03	1.61		18.50	-2.32		11.07	1.04		7.63	-1.89
	13.06	1.58		16.89	-2.24		8.86	1.04		5.89	-1.51
	11.17	1.49		15.14	-2.22		6.48	1.04		4.25	-1.27
	9.76	1.79		13.38	-1.99		4.79	1.43		3.08	-0.22
	7.45	1.75		11.45	-1.61		2.87	1.87			
	5.38	2.26		10.05	-0.70						
	1.68	-1.04		8.94	0.17						
				6.76	0.96	MC Ovis	29.03	-0.29	MC Ovis	30	1.32
MC Ovis	24.36	0.22		5.19	1.56	M3 11134	27.16	-0.70	M3 11138	28.12	1.17
M2 20165	22.35	0.33		3.64	1.09		25.66	-0.96		25.99	0.75
	20.52	1.10					23.73	-1.29		24.09	0.64
	18.91	1.90					21.77	-1.53		22.46	0.27
	17.63	1.89	MC Ovis	25.79	-0.17		20.07	-1.18		20.84	-0.03
	15.53	2.36	M3 11132	23.8	-0.41		18.33	-0.57		19.15	-0.25
	14.1	2.57		22.22	-0.49		16.73	0.34		17.33	-0.87
	12.31	1.87		20.59	-0.81		14.86	0.48		15.49	-1.27
	10.48	1.05		18.66	-0.18		13.03	0.85		13.73	-1.17
	8.55	1.08		17	0.08		11.74	-1.26		11.26	-0.74
	7.10	0.10		14.96	0.56		6.20	0.68		9.94	-0.06
	5.08	-0.59		13.22	0.88		4.43	1.24		7.78	0.65
	3.26	-0.52		10.77	1.02					6.76	1.39
	1.16	0.55		9.27	0.64					4.93	1.19
				7.74	0.64					4.24	0.99
				5.90	0.30					2.32	0.20
				4.45	-0.20						
				3.08	-0.37						

Figure 4.4. Sequential $\delta^{18}\text{O}_{\text{V-PDB}}$ values measured on enamel bioapatite of sheep second and third molars.

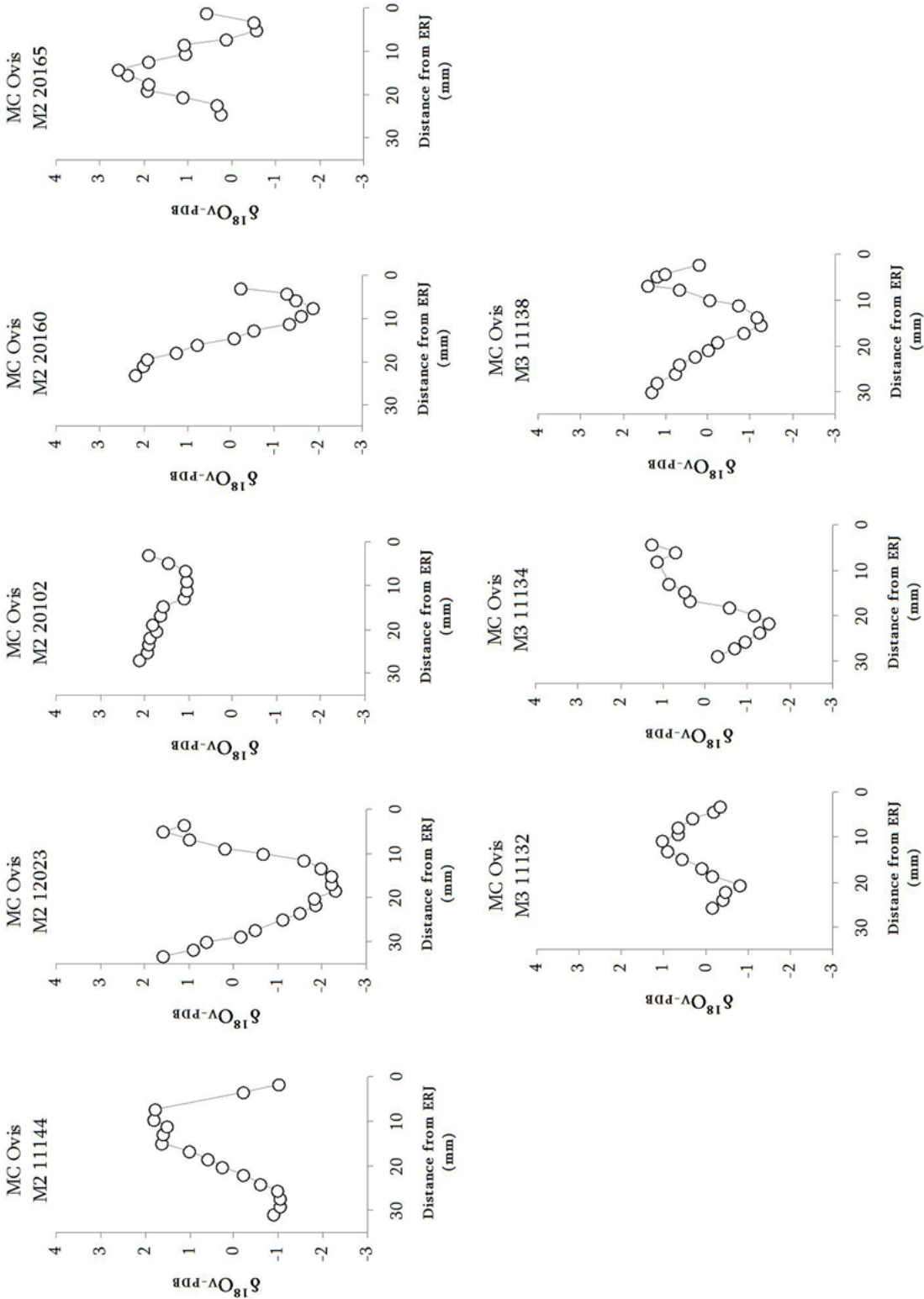


Table 4.4. Results from the calculation of the best fit (by method of least squares) for combined variation of X (period), A (amplitude), x_0 (delay) and M (mean). The Pearson's correlation coefficient (R) is also indicated.

Specimens	X (mm)	A (%)	x_0 (mm)	M (%)	R	x_0/X
MC <i>Ovis</i> M2 20160	28.94	2	22.20	0.2	0.998	0.77
MC <i>Ovis</i> M2 20165	21.67	1.4	15.26	1.1	0.967	0.70
MC <i>Ovis</i> M2 20102	25.94	0.4	22.43	1.5	0.953	0.86
MC <i>Ovis</i> M2 12023	25.03	1.9	3.86	-0.6	0.989	0.15
MC <i>Ovis</i> M2 11144	30.29	1.5	12.30	0.3	0.975	0.41
MC <i>Ovis</i> M3 11132	21.33	0.8	11.21	0.2	0.980	0.53
MC <i>Ovis</i> M3 11134	28.25	1.3	9.06	0	0.959	0.32
MC <i>Ovis</i> M3 11138	19.45	1.2	5.53	-0.1	0.963	0.28
Mean	25.11	1.3	12.7	0.3	Max	0.86
Δ	3.97	0.52	6.94	0.67	Min	0.15

5. Discussion

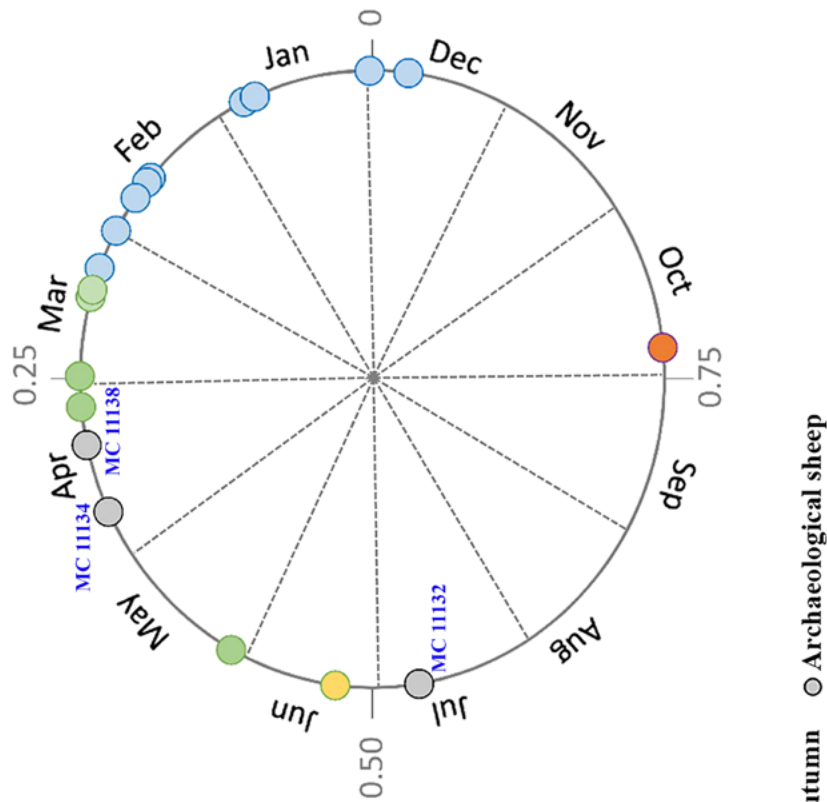
At Mas Castellar de Pontós sheep births show a seasonal bi-modulated reproductive pattern, with lambing occurring both from the late winter to the late spring and in the autumn. In high and mid temperate latitudes (Hafez 1952; Jewell & Grubb 1974; Santiago-Moreno *et al.* 2006; Gootwine E. 2011; Gómez-Brunet *et al.* 2012), the natural sheep lambing season occurs from late winter to spring. Therefore, births occurring in autumn represent an extension of the natural breeding season and, consequently, an extended fertility period.

Nowadays, autumn births in the Western Mediterranean region are currently practised and typical of farming systems. The capacity of the Late Iron Age sheep to give birth in autumn is not surprising, since the earliest evidence of this practice in this area has been found at Taï and Gazel (Tornero *et al.* 2020), and dates back to the Early Neolithic. Isolated cases of autumnal lambing have been reported in the Early Neolithic site of Chaves (Sierra *et al.* 2021), during the Middle and Late Neolithic phases at Els Trocs (Tejedor-Rodríguez *et al.* 2021), in the Middle Neolithic site of Auriac (Fabre *et al.* 2021) and at Llo during the Middle/Late Bronze Age (Knockaert

et al. 2018). At present, stable isotope data on reproductive strategies for protohistoric chronologies in the Western Mediterranean region are still very limited. Therefore, the results presented here provide the first innovative evidence of sheep's seasonal reproductive patterns also during the Late Iron Age.

Spring mating, and subsequently autumnal lambing, implies specific attention and management of the livestock and extensive knowledge of the timing of the fertility cycle in ewes by herders. Control of the interaction between females and males is required, bringing them together at a specific time, i.e., at the end of the fertility period (Tornero *et al.* 2020). An additional prerequisite for "out-of-season" births is the availability of fodder resources during lactation in autumn and winter. Evidence of reproductive behaviour with autumnal lambing in Mas Castellar suggests that the herders were able to provide adequate fodder resources necessary for lactation, as a consequence of suitable climatic conditions. Indeed, during the Iberian-Roman period the whole Mediterranean basin was characterised by warmer and/or moister conditions, particularly in the north-western Mediterranean, and by a strong seasonality with frequent

Third Molars (M_3)



Second Molars (M_2)

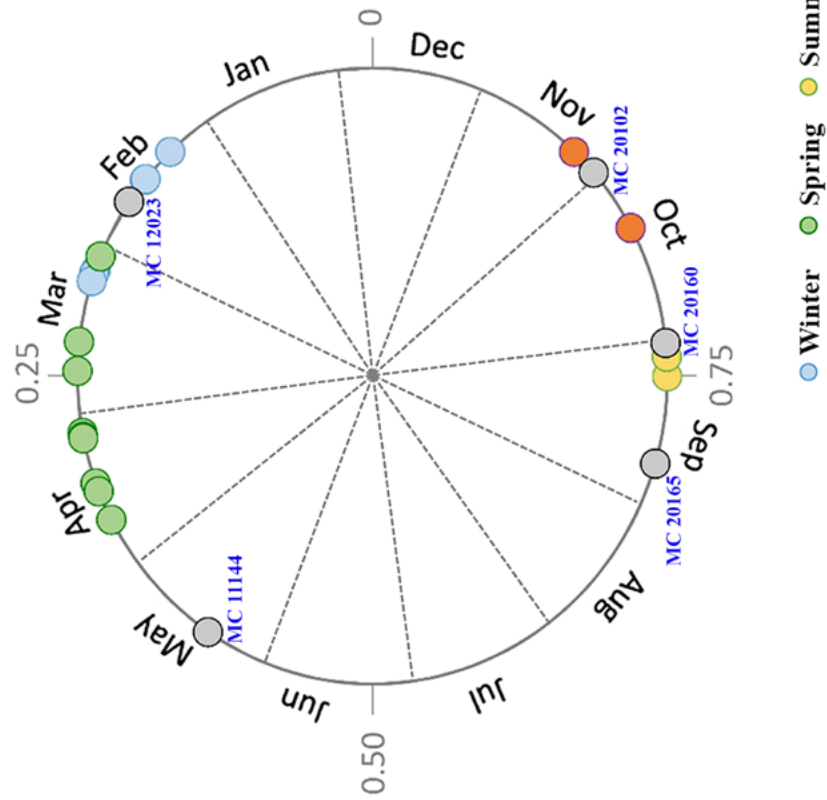


Figure 4.5. Distribution of sheep births at Mas Castellar de Pontós, as reflected by the position of the maximum $\delta^{18}O$ value in M_2 and M_3 tooth crown (x_0) normalized to the period of the cycle (X). The birth season is compared with modern reference populations with known date of birth and potential agreement with successive calendar months (Blaise & Balasse 2011, Balasse et al. 2012, Balasse et al. 2017, Tornero et al. 2018 and Balasse et al. 2020). Archaeological sheep are represented in grey dots, while the modern ones in colored dots.

precipitation events in the cold season (González-Sampériz *et al.* 2017). This could have provided secure availability of pasture resources to support autumn and winter lactation. Furthermore, the herd could be fed with the integration of fodder from cereal cultivation.

Moreover, the presence of two different birth seasons strongly suggests a division of the herd into two groups of females giving birth at different times of the year (Tornero *et al.* 2020). Furthermore, autumn births occurred in a quite narrow period of time (almost two months) suggesting the results of synchronised strategy by herders. Birth synchronisation by herders allows them to concentrate all the efforts required to monitor lambing and take care of the youngest animals at a given time (Balasse *et al.* 2020).

Finally, “out-of-season” lambing manipulated by herders was probably dictated by a husbandry strategy aimed at the intensive exploitation of secondary products, available throughout the year (Gómez Brunet *et al.* 2012). This hypothesis is further supported by the results of zooarchaeological studies on the faunal remains from the rural establishment (Colominas 2008; Colominas 2013), according to which caprine livestock was mainly exploited to obtain secondary products, such as milk and wool, testified by a predominance of mostly adult female individuals.

The existence of two different reproductive seasons could also have been aimed at increasing the herd size. This practice would have allowed the constant availability of a sufficient number of individuals to be sacrificed or exploited during their lifetime or to be used as trading products. In this regard, the hypothetical approximation of the herd size present in the rural establishment during its period of

occupation refers to a flock of about 60-80 individuals (Colominas 2013).

6. Conclusion

The first study on seasonal reproductive patterns adopted by the community that inhabited Mas Castellar de Pontós during the Late Iron Age is presented in this paper. Based on the results obtained, a first glimpse of the complexity of the organisation and management of livestock by these societies can be carried out.

Results of the sequential oxygen isotope analyses in the second and third molars of sheep from Mas Castellar de Pontós show that both natural (late winter/spring) and “out-of-season” (autumn) births are attested. Moreover, autumnal lambing occurred within a narrow period of time. This flock management, strongly manipulated by anthropic intervention, was probably directed to the exploitation of a large herd, divided into two distinct groups and with off-season forage available during lactation in the winter period. The huge technical effort expended by the shepherds operating the rural establishment was compensated by the availability of diversified secondary products throughout the year. Thus, the management planned for the herd in Mas Castellar was related to the type of exploitation desired. The rural establishment, whose main function was to accumulate and redistribute cereals, probably included people dedicated exclusively to planning the management and exploitation of livestock (Colominas 2013), starting from the control of reproduction calendars.

The results obtained for Mas Castellar de Pontós need to be complemented by further in-process studies related to livestock diet and mobility.

Nevertheless, the present study proves that the potential of data that can be achieved by using biogeochemical analyses in protohistoric chronologies in the Iberian Peninsula is enormous. Indeed, extending the studies to other types of settlement is required to obtain a complete and precise picture of the different livestock strategies adopted by each community in relation to its own ecological conditions and needs.

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4.1.2 Paper 1b. Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula (3rd c. BC)

This publication reports a more detailed view of the season and seasonality of sheep births and the duration of the lambing period among Iron Age Iberian communities. Along with increasing the number of teeth analysed for the Mas Castellar de Pontós site, the sequential analysis was also performed on the second and third molars from the remaining three sites studied in this thesis: Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira. Furthermore, for the first time, this study integrates data from sheep's second and third molars with a solid basis for interpretation, following the modern reference set recently published by Balasse and colleagues (2023).

The results reveal diverse reproductive patterns and distinct demographic management of sheep in the four investigated settlements, with manipulations on both the season and duration of the lambing period. Therefore, this study indicates that the management and exploitation of herds were determined by the specific economic needs, social organisation, and environmental conditions of each settlement. The biogeochemical approach has provided more comprehensive information than traditional zooarchaeological studies, highlighting the importance of livestock husbandry in the economy of the Iron Age Iberian communities.

Finally, from a methodological perspective, the data obtained from the sequential analysis of the M₃s provided a lower seasonal resolution compared to those obtained from the M₂s. Consequently, inter-individual

variability in the timing of third molar growth may generate different levels of inaccuracy in interpreting the results. Nevertheless, this discrepancy does not result in the misattribution of an individual's birth group (natural vs. 'out-of-season' births).

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RESEARCH



Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula (3rd c. BC)

Chiara Messina^{1,2} · Carlos Tornero^{1,3} · Lidia Colominas⁴

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Abstract

Isotopic analyses have proven to be an essential tool for obtaining more comprehensive and precise knowledge about past livestock strategies. Nevertheless, biogeochemical data for the Iron Age and, in particular, for the Iberian Peninsula are still very scarce. This study aims to provide a first and pivotal glimpse of sheep reproductive strategies adopted by north-eastern Iberian societies during the Middle and Late Iron Age, a period in which a process of urbanisation and agricultural expansion took place. Birth seasonality and the duration of the lambing period are here investigated through sequential oxygen isotope analyses performed on sheep's second and third lower molars from four relevant Catalan sites (Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, Turó de la Rovira). These are contemporary (third century BC) and are located in different ecological and cultural areas. Results display diversified sheep reproductive patterns and distinct demographical management in the four settlements, with manipulations both on the season and on the duration of the lambing period. Thus, we propose that herd management and exploitation were determined by specific economic demands and the social organisation and environmental conditions of each area. Therefore, through this biogeochemical approach, we have been able to demonstrate that the resources, knowledge and time involved in the organisation of sheep husbandry were much more complex and planned than classical zooarchaeological studies have so far documented, highlighting the importance of livestock farming as a key activity in the economy of the Iron Age Iberian communities.

Keywords Stable oxygen isotopes · Birth seasonality · Lambing period · Animal husbandry strategies · Middle-Late Iron Age · NE Iberian Peninsula

Introduction and research objectives

Historical context and aim of the research project

Since the Middle Iron Age and until the Roman conquest, the north-eastern (NE) Iberian societies were characterised by a proto-state structure, strongly hierarchical and arranged into different centralised political entities (Gracia 2005; Sanmartí 2014, 2021). In this context, a wide set of interconnected open-air settlements with specific functions emerged: i.e. fortified centres, rural establishments, small villages and silo fields (Gracia 2005; Sanmartí 2014, 2021). All of them were structured around the so-called first-order cities, central nuclei whose main function was the control and centralisation of agricultural production (Asensio et al. 1998; Bouso et al. 2000; Sanmartí 2004, 2014; Sanmartí et al. 2019). These communities developed a predominantly local agricultural economy devoted to self-sufficiency where cereal

✉ Chiara Messina
 cmessana@iphes.cat

✉ Carlos Tornero
 Carlos.Tornero@uab.cat

¹ Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, ES, Spain

² Departament d'Història i Història de L'Art, Universitat Rovira i Virgili (URV), Avinguda de Catalunya 35, 43002 Tarragona, ES, Spain

³ Department of Prehistory, Facultat de Filosofia i Lletres, Autonomous University of Barcelona (UAB), Edifici B, 08193 Bellaterra, ES, Spain

⁴ Institut Català d'Arqueologia Clàssica (ICAC-CERCA), Plaça d'en Rovellat S/N, 43003 Tarragona, ES, Spain

surplus represented the main exchange product (Asensio et al. 2003a; Asensio 2013; Prats et al. 2020).

Livestock husbandry was another key activity among the subsistence strategies of these communities. This NE Iberian husbandry was mostly specialised in caprines, with a predominance of sheep (Franquesa et al. 2000; Perez et al. 2007; Colominas 2008a; Colominas et al. 2011), probably due to its capacity to produce a broad variety of products (i.e. meat, milk, wool, manure) and for its great adaptability to different environmental constraints (Albizuri and Nadal 1999; Rasali et al. 2006; Colominas 2006; Perez et al. 2007). The adoption of diversified and selective livestock strategies aimed at self-sufficiency and suited to the necessities of each settlement has been demonstrated by the results of zooarchaeological studies carried out so far (Albizuri and Nadal 1999; Franquesa et al. 2000; Colominas 2008b, 2013a; Colominas et al. 2019; Nieto Espinet et al. 2021). However, despite this self-sufficiency, a general ever-increasing tendency towards a specialisation in secondary products is also detected (Franquesa et al. 2000; Colominas 2006; Colominas et al. 2011). In this scenario, obtaining a more comprehensive and, at the same time, more precise knowledge about the different livestock strategies adopted by Iberian Iron Age societies is necessary.

In order to achieve this, in this study, we apply a biogeochemical approach investigating sheep seasonal reproductive strategies in four Middle/Late Iron Age settlements located in the northeast of the Iberian Peninsula (present-day Catalonia). Season and seasonality of sheep birth are examined to explain how Iberian shepherders managed control of reproductive cycles. Our study will allow detecting if different reproduction patterns within the same settlement exist and if this key-diagnostic aspect of sheep management was performed differently at each site. Evidence of those practices is crucial to identify how pastoralist labour was managed and how the production of meat, milk and other products was organised (Balasse et al. 2003). This data provides valuable information about livestock management and exploitation strategies developed by the Iberian communities. Since biogeochemical data are still very scarce for protohistoric periods and, in particular, for the Iberian Peninsula, the present study also aims to begin to fill the lack of stable isotope results about the Iron Age Iberian societies.

Seasonal reproductive patterns inferred by sequential $\delta^{18}\text{O}$ values

Biogeochemical data and stable isotope analyses have proven to be fundamental tools for complementing and enriching traditional zooarchaeological studies reconstructing past husbandry strategies. With a seasonal time-scale resolution, sequential or dental series of oxygen isotope values from sheep molars enamel can provide innovative life history data

about past herds (Balasse 2002). Once mineralised, tooth enamel does not turn over and reflects the isotopic signal registered during its formation. The oxygen isotope composition measured in the tooth enamel mineral fraction (i.e. bioapatite compound) is mainly derived from ingested water and plants consumption (Longinelli 1984; Luz et al. 1984), and these isotopic signatures are well-related to the meteoric water and temperature, which, in temperate latitudes, vary according to the seasonal changes. At mid and high latitudes, higher $\delta^{18}\text{O}$ values reflect the warmer season, whilst the coldest one is recorded by lower $\delta^{18}\text{O}$ values (Gat 1980). Through the $\delta^{18}\text{O}$ sequences recorded in each tooth crown, the seasonality and reproductive dynamics of the sampled sheep specimens are investigated using the position of the maximum and minimum seasonal climatic events along the tooth crown.

The season of birth of archaeological sheep specimens can also be inferred using sequential series of $\delta^{18}\text{O}$ values. Similar sinusoidal variations of warm and cold episodes between different sampled individuals would indicate synchronised births, whilst divergences may indicate different birth seasons. However, dental crown height may vary between individuals (Balasse et al. 2012), affecting sequential $\delta^{18}\text{O}$ series and inter-individual variability. Therefore, in order to compare the placement of oxygen sequences between individuals, it is necessary to eliminate the bias associated with tooth size variability and normalise the distances (Knockaert 2017). Using the method proposed by Balasse and colleagues (2012), it is possible to model the sequences and to describe and compare the data obtained objectively (Tornerio et al. 2013). Finally, to infer an individual's season of birth, it is necessary to consider the delay in enamel mineralisation, which affects the recording of the isotopic signal in the crown (Balasse et al. 2012). For this reason, it is indispensable to use modern sheep populations with known season of birth. These references make it possible to place the birth seasons of archaeological individuals within an annual calendar and hence understand the distribution of births within past societies' herds (Knockaert 2017). Reference data are currently available for both M_2 and M_3 ; a higher inter-individual variability in the timing of M_3 formation has been observed, resulting in a lower resolution at the time of defining the birth calendar. In this study, the reliability of M_3 s for defining the birth calendar of archaeological individuals is tested.

Season and seasonality of sheep birth have been investigated in zooarchaeological studies with increasing interest during the last decade. Knowing the timing and the length of the caprine lambing season during the year is indeed essential for fully interpreting the ancient pastoral societies' practices (Balasse et al. 2017; Knockaert 2017). So far, a significant focus has been placed on archaeological sites in Europe and the Near East, dating from the 6th to the

3rd millennium B.C. (Torneró 2011; Torneró et al. 2016; Hadjikoumis et al. 2019), to shed light on domestication's origin and early development. These studies have shown that human intervention in sheep populations favoured a prolongation in the duration of the birth period and, consequently, an extension of the period of sexual activity (Balasse et al. 2017). Furthermore, it has been possible to trace the earliest evidence of out-of-season births (during autumn) in the western Mediterranean, at the two Early Neolithic sites of Taï and Gazel, in Southern France (Torneró et al. 2020); this demonstrated that the capability of de-seasoning births was already present, at least, in the second half of the 6th millennium BC in the Western Mediterranean.

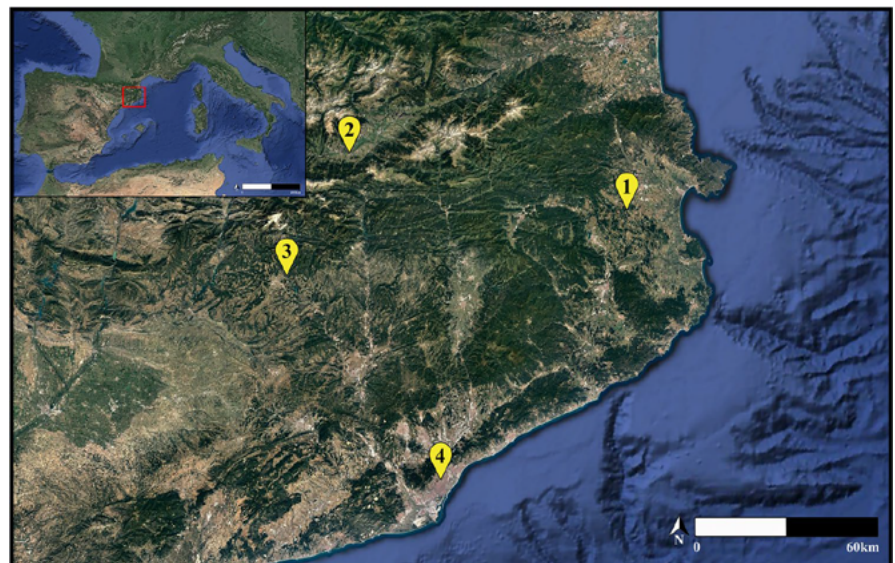
Sites

Samples selected proceed from archaeological sites with contemporaneous and well-dated occupations along the third century BC. All sites are open-air settlements located in distinct ecological and cultural areas within the north-east of the Iberian Peninsula (Fig. 1). Mas Castellar de Pontós is located on a fertile plain in the northern pre-coastal area, in the territory of Indigeti; at higher altitude is the Ceretan settlement of Tossal de Baltarga, on the Cerdanya plain; moving inland there is Sant Esteve d'Olius in the Pre-Pyrenees area, on the fertile Lacetan agricultural plain; and finally, close to the central Mediterranean coast, the Laietan site of Turó de la Rovira extends over the Barcelona plain. In all settlements, agriculture has been traditionally described as the main economic activity within subsistence strategies, documenting management, production, storage and distribution of agricultural surplus (Pons et al. 2010;

Morera 2017; Asensio et al. 2008). In the Iberian period, crops in the north-eastern Iberian Peninsula were dominated by wheat (*Triticum aestivum/durum*) and barley (*Hordeum vulgare*) and, secondarily, by millet (*Panicum miliaceum*) and leguminous plants (*Lens culinaris*, *Pisum sativum*, *Vicia faba*) suggesting the use of rotation cycles in the cultivations (Alonso 2000; Riera et al. 2020).

Mas Castellar de Pontós is located on the Empordà plain (Girona, highest altitude: 154 m. a.s.l.; Fig. 2), approximately 17 km equidistant from the Greek colonies of *Rhode* and *Emporion*. Being located on a promontory between two waterways, a tributary of the Muga and the river Fluvià, and close to the coast makes it a strategic point of communication between the coast and the interior, as well as between the two Greek colonies and the indigenous inhabitants (Pons et al. 2010). Along with the geographical factor, the humid and mild climate favoured the development of an important economic centre with a rural focus throughout the Iron Age (Pons et al. 2010). Human occupation covers a wide chronological frame, between the end of the seventh century and the beginning of the second century BC (Pons et al. 2010; Adroher and Pons 2002). The so-called rural establishment, a specialised agricultural settlement, was occupied between 250 and 180 BC. Associated with the rural establishment was an extensive silo field (Pons et al. 2010). Managed by a rural aristocracy, the settlement was an important commercial enclave for cereal production and a major reserve centre for the entire *Emporion* area (Fuertes et al. 2002; Bouso et al. 2000). Carpological data attest to the presence of both winter (wheat and emmer) and spring (millet, fox-tail millet, barley, oats) crops, combined, in minor quantities, with the cultivation of legumes (pea, lentil) and grapes (Canal 2000, 2002). Production probably involved a variety

Fig. 1 Location of the four archaeological sites included in this study: (1) Mas Castellar de Pontós, (2) Tossal de Baltarga, (3) Sant Esteve d'Olius and (4) Turó de la Rovira (Google Earth Pro modified)



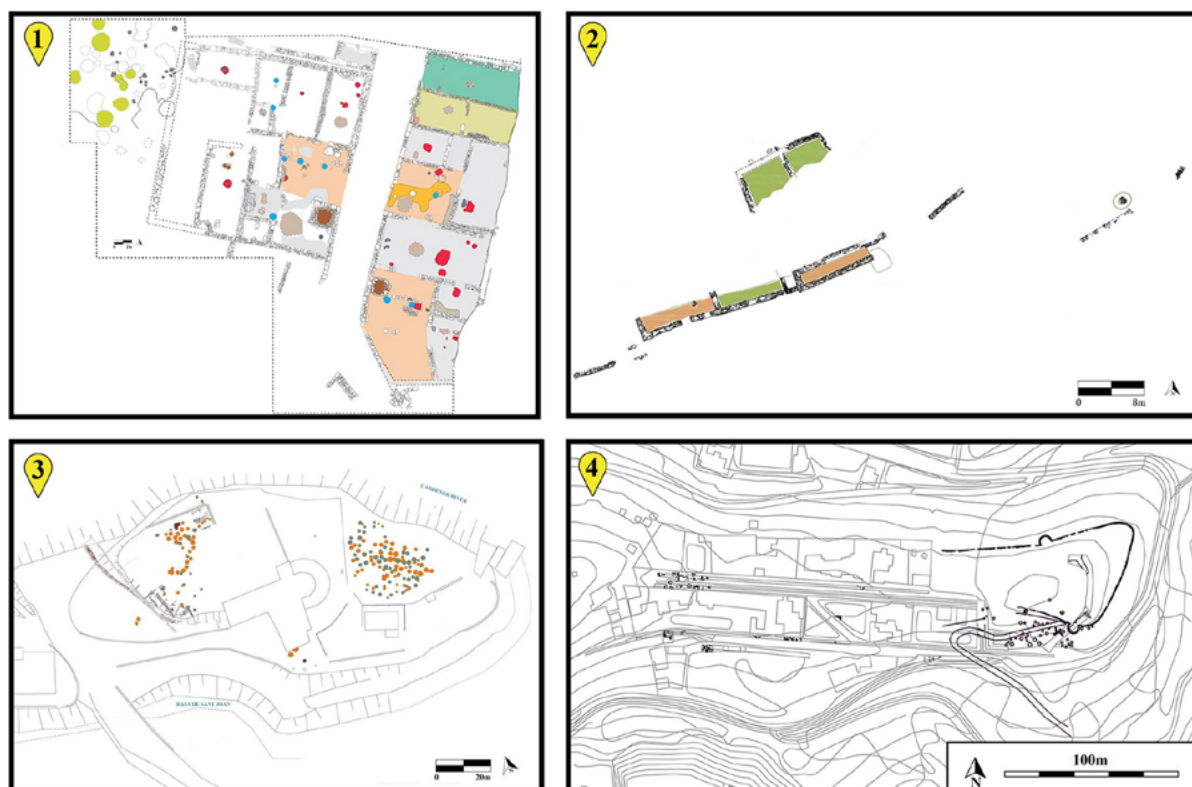


Fig. 2 Plans of the four archaeological sites: (1) Mas Castellar de Pontós (Garcia-Dalmau C., modified), (2) Tossal de Baltarga (Oller et al. 2021, modified), (3) Sant Esteve d'Olius (Morera de Llorens et al. 2016, modified) and (4) Turó de la Rovira (Giner Iranzo D., modified)

of crop management strategies, including both rotation systems (biennial and triennial) and the joint sowing of different species, such as foxtail millet and barley (Alonso 2000; Canal 2000).

The site of Tossal de Baltarga (Bellver de Cerdanya, 1166 m. a.s.l.; Fig. 2) is a high mountain settlement in the eastern Catalan Pyrenees, with a territorial control purpose of the routes crossing this area. Indeed, its position on the top of a hill allowed control over the land route and the crossing of the river Segre (Colominas et al. *in press*). Chronologically, it revealed three different phases, from the Late Bronze Age to the Republican Roman period (Morera 2017). During the Iberian phase (fourth to third century BC), the settlement is characterised by several residential and working buildings (Morera 2017; Colominas et al. *in press*). At the end of the third century BC, the site, with a certain social and economic relevance within the Cerdan population, was violently destroyed by fire (Morera 2017). The albeit limited carpological data from one of the buildings attest to the presence of barley, wheat, millet and einkorn (Colominas et al. *in press*). Large ceramic containers and concentrations of wheat grains were recovered from another building of the settlement, indicating a probable

storage function (Olesti et al. 2018). Indeed, during the Iberian period, there was an increase in agricultural production in the Cerdanya plain, favoured by the generally dry climate but with abundant water sources (Morera 2017; Olesti and Mercadal 2017).

Sant Esteve d'Olius (Solsonès, 664 m a.s.l.; Fig. 2) is a village in the inland of the Catalan region. It is placed on the highest point of a small promontory, bordered by the river Cardener, the main communication way to the coast (Asensio et al. 2003b). The Iberian phase (3rd c. BC) is characterised by a fortified settlement specialised in the storage and management of cereal surpluses, with silo fields and residential buildings (Asensio et al. 2003b; Chorén and Caldach 2006; López 2009). The larger extension of silo fields compared to habitat structures reveals the prominence of agricultural activities in the settlement, favoured by the extension of the fertile plain irrigated by the river Cardener (Asensio et al. 2008). These types of strategic nuclei specialised in cereal storage are well known along the Iberian coastal areas, whilst they are exceptional in the interior, as in the case of Sant Esteve d'Olius (López 2009). The archaeobotanical data from the silos revealed a large quantity of barley remains and, in considerably minor quantities, wheat

and emmer and traces of leguminous plants (pea and lentil). In general, the most represented are winter cereals, with a monospecific concentration of barley (López 2009).

The fortified settlement of Turó de la Rovira (mid-third century BC to late third/early second century BC) occupies the top of the homonymous plain situated in Barcelona (Barcelonès, 262 m. a.s.l.; Fig. 2; Colominas i Roca 1954; Giner 2018). Delimited by a wall, it is associated with a moat on the south-eastern side, two silo fields concentrated on the two sides of the village, and residential buildings on the southern slope (Giner 2018). The settlement has been interpreted as a second-order village of the Laietan territory, with a dominant position over neighbouring minor centres (Giner 2018). The environment was open and deforested, probably due to the presence of cultivated fields all around (Riera et al. 2020). Carpological data show agriculture with a predominance of wheat and barley and the presence of millet and, in minor quantities, legumes, grapes and figs (Riera et al. 2020).

Material and methods

Materials

A total number of 31 lower molars (18 second molars and 13 third molars) of 22 sheep (*Ovis aries*, Linnaeus, 1758)

from four different archaeological sites were selected and analysed for this study. Ten second molars and seven third molars were extracted from mandibles, whilst all the others were isolated teeth. All selected molars present completely or almost fully formed crowns and early wear stages. Five second molars (MC *Ovis* 11144, MC *Ovis* 12023, MC *Ovis* 20102, MC *Ovis* 20160, MC *Ovis* 20165) and three third molars (MC *Ovis* 11132, MC *Ovis* 11134, MC *Ovis* 11138) here included were already used for analysis in a preliminary study (Messana et al. in press). Descriptive information (side, wear stage and estimated age of death) about the teeth selected for this study is presented in Table 1.

Methods

After cleaning the selected teeth surface by abrasion with a tungsten drill, enamel bands were sequentially sampled using a diamond bit. Sampling was performed on the buccal side, on the posterior lobe of M₂ and on the middle lobe of M₃. All the samples were taken at 1–2 mm intervals along the whole crown height, starting from the apex. Positions of sample bands were recorded in mm from the enamel-root junction (ERJ).

Between 10 and 20 samples per tooth were sampled, resulting in a total number of 473 samples. Powdered enamel samples (weighing between 2.5 and 13.7 mg) were chemically treated at the Biomolecular Laboratory of the Institut Català

Table 1 Sheep (ID), sampled teeth and estimated age of death of sampled specimens from the four archaeological sites included in this study: Mas Castellar de Pontós (MC), Tossal de Baltarga (BTB), Sant Esteve d'Olius (O) and Turó de la Rovira (TR). Side (L, left; R, right); wear stages, according to S. Payne (1973); na, no analysed. Estimated age of death following criteria and codes from Payne (1973)

Site	Sheep ID	Side	M ₂		M ₃	
			Wear stage	Age estimation	Wear stage	Age estimation
MC	11144	L	F	2–6 years	na	na
	12023	L	E	2–3 years	na	na
	20102	L	E	2–3 years	na	na
	20160	R	E	2–3 years	F	3–4 years
	20165	R	F	3–4 years	F	3–4 years
	11132	R	na	na	G	4–6 years
	11134	L	na	na	G	4–6 years
	11138	L	na	na	G	4–6 years
BTB	3249	R	E	2–3 years	na	na
	3270	R	F	3–4 years	F	3–4 years
	3271	L	D	21–24 months	na	na
	3031	L	na	na	F	3–4 years
O	174	L	E	2–3 years	na	na
	205	R	E	2–3 years	E	2–3 years
	318	R	G	4–5 years	G	4–5 years
	348	R	F	4–6 years	na	na
	478	L	E	2–3 years	E	2–3 years
	482	R	F	4–6 years	na	na
	484	R	F	4–6 years	na	na
TR	725	R	F	3–4 years	F	3–4 years
	763	L	F	3–4 years	F	3–4 years
	831	L	E	2–3 years	E	2–3 years

de Paleoeecologia Humana i Evolució Social (IPHES-CERCA), following the protocol described in Balasse et al. (2002) and modified by Tornero et al. (2013). Samples were treated to eliminate contamination from exogenous carbonates (4 h in 0.1 M acetic acid (CH_3COOH); 0.1 ml solution/mg of sample), rinsed several times in distilled water and dried in an oven at 70 °C for 48 h.

Treated samples were measured using an automated carbonate preparation device (KIEL-III) interfaced to a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Dept. of Geosciences), University of Arizona (USA), with scientific supervision from Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70 °C. The accuracy and precision of measurements were checked and calibrated using NBS-19 and NBS-18 international standards. The mean analytical precision within each run and from replicate measurements of standards during analysis varies $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.08\text{‰}$ for $\delta^{13}\text{C}$ (1 sigma). Isotope composition is reported in δ notation and expressed per mil (‰), in agreement with the corrections from standard V-PDB (Vienna-Pee Dee Belemnite) oxygen values.

Seasonal reproduction patterns were assessed following Balasse et al. 2003, 2012, and Tornero et al. 2013. In order to quantify the inter-individual variability in tooth size and to define the position of the maximum $\delta^{18}\text{O}$ value in the tooth crown (x_0/X), the $\delta^{18}\text{O}$ sequences were modelled using the equation described by Balasse et al. 2012, based on a cosine function. The model includes four parameters for M_2 modelling: the period of the cycle (X), expressed in mm and corresponding to the length of tooth crown potentially formed over a year; the amplitude of the isotopic signal (A), expressed in ‰; the delay (x_0) expressed in mm, corresponding to the position in tooth crown where the $\delta^{18}\text{O}$ has his maximum value; and the mean (M), expressed in ‰. For the modelling of M_3 , four more parameters are added: the slope of the mean (p), expressed in mm; the signal attenuation (x_A) and the lateral shift (x_B) of the amplitude, both expressed in mm; the gradation of the period (b). As a consequence of the addition of parameter b , the normalised period for M_3 is given by x_0/X_{real} .

As the inter-variability in (x_0/X) reflects the variability in the birth season, this latter is estimated by comparison with data from modern sheep populations with the known date of birth. These reference data included individuals from Blaise and Balasse 2011, Balasse et al. 2012, Balasse et al. 2017, Balasse et al. 2020, Balasse et al. 2023 and Tornero et al. 2018.

Results

Oxygen isotope ratios

Results of the intra-tooth sequences of $\delta^{18}\text{O}$ values are summarised in Table 2 and comprehensively presented in

Table S1 and Figure S1. The mean $\delta^{18}\text{O}$ value from all samples is $0.4 \pm 1.6\text{‰}$, ranging from 2.6 to -4.6‰ . The mean $\delta^{18}\text{O}$ value within each specimen varies from 1.6 to -2.9‰ , maximum values range from 2.6 to -1‰ , minimum values range from 1‰ to -4.6‰ and the amplitude varies between 1.1 and 6‰ .

Modelling of sequential $\delta^{18}\text{O}$ series

The results of the modelling of oxygen sequences are presented in Table S2 for the M_2 and in Table S3 for the M_3 .

Oxygen sequences obtained in the M_2 could be all modelled except for the tooth O M2 348. Normalised results

Table 2 Summarised isotopic results ($\delta^{18}\text{O}$ values) in bioapatite samples from archaeological lower second (M_2) and third (M_3) sheep molars: mean, range, maximum (max) and minimum (min) isotopic values

Teeth	n	$\delta^{18}\text{O}_{\text{V-PDB}\text{‰}}$			
		Mean	Range	Max	Min
MC M2 11144	16	0.2	2.8	1.8	-1
MC M2 12023	19	-0.6	3.9	1.6	-2.3
MC M2 20102	14	1.6	1.1	2.1	1
MC M2 20160	13	0	4.1	2.2	-1.9
MC M2 20165	14	1	3.2	2.6	-0.6
MC M3 11132	14	0	2.3	1	-1.2
MC M3 11134	13	-0.1	2.8	1.2	1.5
MC M3 11138	17	0.2	2.7	1.4	-1.3
MC M3 20160	15	-0.6	2.9	0.5	-2.4
MC M3 20165	15	-0.3	2.6	0.9	-1.6
BTB M2 3249	16	-1.8	6	1.4	-4.6
BTB M2 3270	10	-0.6	3.9	0.9	-3
BTB M2 3271	13	-2.2	5.1	0.6	-4.5
BTB M3 3031	16	-1.3	4.6	1.1	-3.5
BTB M3 3270	12	-2	7	3.4	-3.6
O M2 174	18	-1.1	4.2	1	-3.2
O M2 205	15	-2.9	3.3	-0.8	-4.1
O M2 318	13	-1	3.4	0.3	-3
O M2 348	15	-2	2.9	-1	-3.9
O M2 478	16	-0.8	3.9	0.9	-3
O M2 482	16	-1.3	4	0.8	-3.2
O M2 484	14	-2.3	2.9	-0.7	-3.6
O M3 205	19	0.2	4	2.5	-1.6
O M3 318	20	-0.6	4.3	1.9	-2.4
O M3 478	14	0	5.2	2.1	-3.1
TR M2 725	18	0.6	2.2	1.9	-0.4
TR M2 763	17	0.9	2.6	2.2	-0.4
TR M2 831	17	0.9	2.3	2.4	0.1
TR M3 725	16	0.8	2	1.9	-0.1
TR M3 763	15	1.3	2.5	2.6	0.1
TR M3 831	13	0.6	2.4	1.4	-1

(x_0/X) for the M_2 are presented in Fig. 3. In Mas Castellar de Pontós, M_2 specimens show an x_0/X ratio that varies between 0.19 and 0.80, indicating a wide distribution of births over the annual cycle. Indeed, the results suggest that lambing occurred from autumn to the late spring. For sheep born in autumn (MC M2 20102, MC M2 20160, MC M2 20165), the duration of the lambing period can be estimated to be just over a month (0.10 years or 1.19 months); whilst for sheep born in spring (MC M2 11144, MC M2 12023), the duration of the lambing period can be estimated to 3 months (0.24 years or 2.93 months).

At Tossal de Baltarga, the M_2 x_0/X ratio varies between 0.08 and 0.28, with a duration of the lambing period of two and a half months (0.20 years or 2.42 months) and births occurred during late winter and spring seasons.

The M_2 s from Sant Esteve d'Olius, with an x_0/X ratio between 0.06 and 0.48, show a wide lambing season of 5 months (0.42 years or 5.05 months), from winter to early summer.

The M_2 specimens from Turó de la Rovira display an x_0/X ratio ranging from 0.27 to 0.59, showing a lambing period of three and a half months (0.32 years or 3.5 months) from spring to summer.

Oxygen sequences obtained in the M_3 could be all modelled except for the teeth MC M3 20160 and TR M3 831, which provided short sequences and not enough sinusoidal variation in oxygen values. In Mas Castellar de Pontós, the normalised M_3 results (x_0/X_{real}) show individuals that fit well

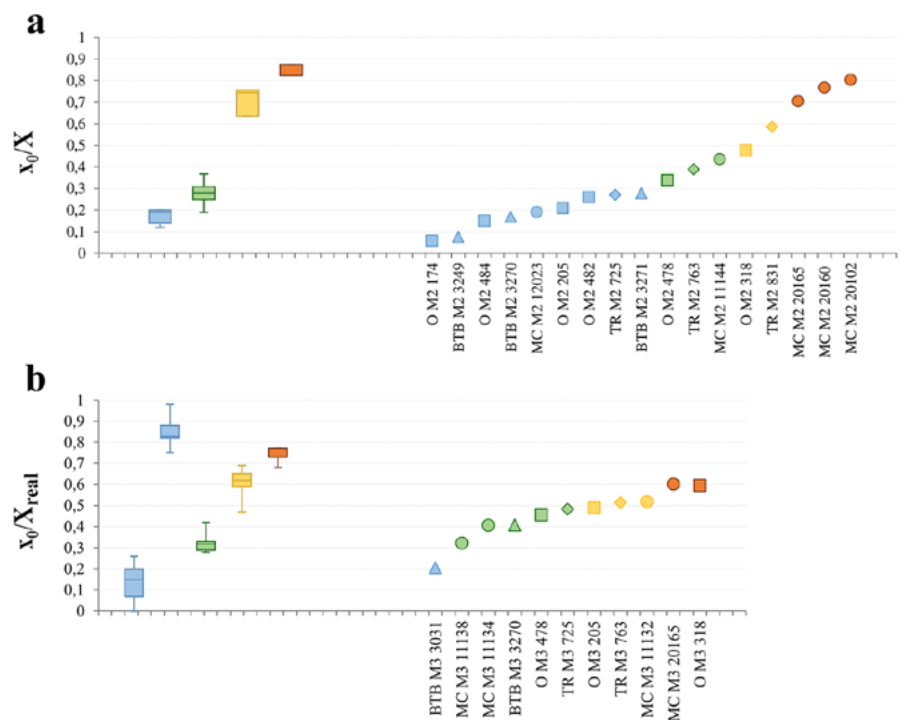
with winter-spring and late summer-autumn periods. At Tossal de Baltarga, the two M_3 specimens record a lambing season occurring exclusively between winter and spring. In Sant Esteve d'Olius, the three M_3 analysed show births occurring during summer and autumn. Finally, the M_3 results from Turó de la Rovira show births occurring during both winter-spring and late summer-autumn periods.

Discussion

Use of M_2 and M_3 at the time of inferring the duration and distribution of seasonal sheep births

Following the recent publication of a new modern reference set by Balasse and colleagues (2023), this study can combine, for the first time, data from second and third molars with a solid basis for interpretation. Results from all M_2 s and M_3 s analysed show that sheep lambing generally occurred all year round in the sites studied (Fig. 3). Beyond these general results, the precisely obtained data from the M_3 s show some divergences from their respective M_2 s, suggesting that the timing of crown formation in M_3 and its inter-individual variability between sampled specimens, may have affected our final interpretations. This observation has already been noticed in both modern (Blaise and Balasse 2011) and archaeological (Tornero et al. 2013) specimens,

Fig. 3 **a** Results of the position in M_2 crown where the highest $\delta^{18}\text{O}_{\text{V-PDB}}$ values are obtained from the modelled datasets, normalised to the period (x_0/X). **b** Results of the position in M_3 crown where the highest $\delta^{18}\text{O}_{\text{V-PDB}}$ values are obtained from the modelled datasets, normalised to the period (x_0/X_{real}). Mas Castellar de Pontós (MC, dots), Tossal de Baltarga (BTB, triangles), Sant Esteve d'Olius (O, squares) and Turó de la Rovira (TR, rhombuses). On the left, season of birth results from modern reference populations: winter (blue), spring (green), summer (yellow), autumn (orange)



affecting this type of approach. Indeed, the results of the M_3 s modelling show a lower seasonal resolution, which results in a higher x_0/X ratio than the birth interval resulting from the respective M_2 s and a narrower birth period. According to Knockaert (2017) and Balasse et al. (2023), it is highly unlikely that inter-individual variability will result in incorrectly attributing a winter/spring birth to an autumn birth and vice versa. As a consequence, spring births should be clearly distinguishable from autumn ones. In our study, data from the archaeological M_3 s show a bi-modal distinction between natural birth (winter/early spring) and out-of-season (late summer/autumn birth), which agrees with the data provided by the M_2 s.

This study includes nine pairs of M_2 s and M_3 s from the same individuals; for seven of them, both M_2 and M_3 could be modelled. All modelled pairs exhibit an average difference of 0.17 (2.02 months) between the results of M_2 (x_0/X) and M_3 (x_0/X_{real}); nevertheless, all pairs of M_3 are in the same seasonal group as their corresponding M_2 , corroborating what Knockaert and Balasse and colleagues stated. In the case of the two unmodelled M_3 s (MC M3 20160 and TR M3 831), the oscillation of their sequence suggests, according to the reference by Balasse et al. (2023), that they belong to the summer/autumn group, the same as their respective M_2 s. Therefore, inter-individual variability in the timing of the third molar growth can generate different levels of inaccuracy; however, these do not result in a misattribution of the birth group. At the time of the interpretation of the archaeological results, the best scenario remains to rely on both M_2 and M_3 . Indeed, the archaeological M_3 display almost the same imprecision shown by modern references. Based on Balasse and colleagues (2023), the inter-individual variability in the M_3 timing of development of modern Lacauene ewes is approximately 1.5 months, whereas modelled and normalised M_2 and M_3 data obtained from individuals of the early 5th millennium cal BC from Cheia (Romania), show a higher variability, but still less than 2 months (1.8 months) (Tornerio et al. 2013; Knockaert 2017). Thus, inter-individual variability bias was apparently present and similar in Iron Age Iberian sheep; moreover, it appears that this was slightly higher than observed in modern and early Eneolithic sheep in Europe.

Due to this methodological constraint, to infer and discuss the timing, duration and distribution of seasonal livestock births, we have chosen to focus on data obtained exclusively from M_2 s.

Season and seasonality of sheep birth

Under temperate climate, sheep lambing season naturally occurs from late winter throughout spring (Hafez 1952; Jewell and Grubb 1974; Santiago-Moreno et al. 2000; Gootwine 2011; Gómez-Brunet et al. 2012). Indeed, in

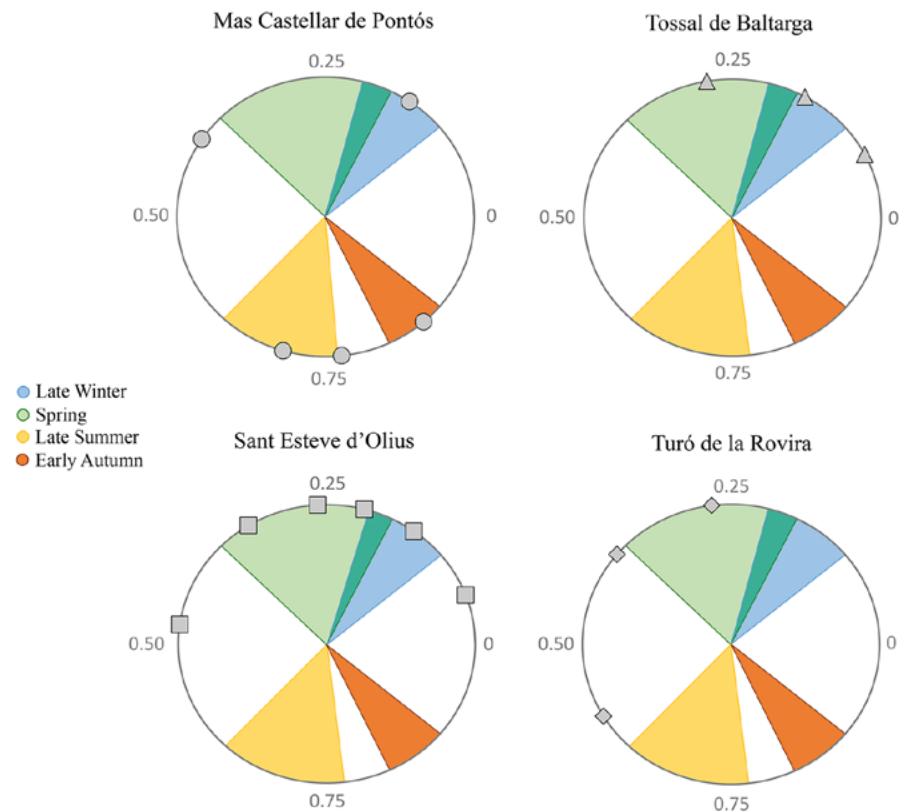
the absence of anthropogenic intervention, this represents the most common pattern in present-day and prehistoric husbandries in temperate Europe (Balasse et al. 2023). Therefore, the significant presence of autumn births necessarily indicates an extension of the natural breeding season and, as a result, a wider fertility period. Nowadays, autumn births are a common occurrence and a feature of farming systems in the Western Mediterranean region. As previously mentioned, the earliest evidence of this practice in this area dates back to the Early Neolithic and has been found at Taï and Gazel (Tornerio et al. 2020). Furthermore, the Early Neolithic site of Chaves (Sierra et al. 2021), the Middle and Late Neolithic phases of Els Trocs (Tejedor-Rodríguez et al. 2021), the Middle Neolithic site of Auriac (Fabre et al. 2021) and Llo during the Middle/Late Bronze Age (Knockaert 2017) are additional isolated cases of site reporting autumnal lambing. Therefore, the interest does not lie in finding evidence of the presence of de-seasonalisation, but rather in verifying its spread and whether it is used systematically or not in the Iron Age and if this was linked to particular socioeconomic circumstances. Given the assumption, the results presented here provide a first evidence of livestock reproductive strategies during the Middle/Late Iron Age period in the Western Mediterranean region.

The seasonal distribution of births at the four archaeological sites is shown in Fig. 4 through a circular graph reflecting a complete annual cycle (Balasse et al. 2020). According to the data, in the north-eastern peninsula dating back to the Mid- and Late Iron Age, sheep births occurred all year round, but with substantial differences in each settlement.

A seasonal bi-modulated reproductive pattern was observed at Mas Castellar de Pontós, where lambing occurred during two different birth seasons: from late winter to late spring and in autumn. Furthermore, autumn births took place in a limited period (just over a month), suggesting the results of synchronised strategy by herders. Here, both “out-of-season” births and their synchronisation are interpreted as the results of herders’ manipulation and deliberate strategic choices. Autumnal lambing, resulting from spring mating, implies a deep understanding and extensive knowledge of sheep reproductive physiology by herders; furthermore, specific attention and management of the livestock are essential. Control of female–male interactions is required, separating rams from ewes and bringing them together at a predetermined time, i.e. at the end of the fertility period (Tornerio et al. 2020; Balasse et al. 2023). The availability of abundant forage resources during autumn/winter lactation represents an additional prerequisite for “out-of-season” births (Tornerio et al. 2020; Balasse et al. 2023).

Tossal the Baltarga provides an entirely different seasonal reproductive pattern. Here, births occurred over a

Fig. 4 Distribution of sheep births in the four study sites, as reflected by the position of the maximum $\delta^{18}\text{O}_{\text{V-PDB}}$ value in M_2 crown (x_0/X). The birth season is compared with modern reference populations with a known date of birth and potential agreement with successive calendar months (Blaise & Balasse 2011, Balasse et al. 2012, Balasse et al. 2017, Tornero et al. 2018 and Balasse et al. 2020). Archaeological sheep are represented in grey shapes, whilst the modern ones, counterclockwise, by blue, green, yellow and orange colour areas



relatively restricted time frame (2.5 months), from late winter to mid-spring, in agreement with the natural sheep lambing season. Therefore, no modifications aimed to extend or shift the expected breeding season due to anthropogenic intervention have been detected. On the other side, a herders' strategy may have resulted in births concentrated in 2.5 months.

The remaining two settlements, Sant Esteve d'Olius and Turó de la Rovira, are characterised by a third, distinct type of reproductive pattern. Due to the herders' interference in sheep reproduction, both settlements exhibit a prolonged lambing period. At Sant Esteve d'Olius, births occurred throughout 5 months, from winter to early summer, with a significantly extended lambing period compared to the natural breeding season. The same pattern is observed at Turó de la Rovira with a 3.5-month-long birth period. Although it is more restricted than Sant Esteve d'Olius', the lambing period is still longer than the natural one and is, therefore, the product of anthropogenic scheduling.

Livestock management and exploitation

Taking into account the data presented and discussed before, we propose that the different strategies deployed in the four

sites are direct consequences of choices dictated by the economy and social organisation of each settlement, and also by the environmental conditions surrounding them. Indeed, results show a great variety in husbandry management and goals.

The most complex herding system is observed at Mas Castellar de Pontós, where the presence of two different birth seasons suggests a division of the herd into two groups of females giving birth at different times of the year. Herders probably regulated "out-of-season" lambing as part of a husbandry strategy aimed at the intensive exploitation of year-round secondary products (Gómez Brunet et al. 2012; Messana et al. *in press*). The results of zooarchaeological studies conducted on the faunal remains provide additional support for this hypothesis (Colominas 2008b, 2013a): indeed, the data suggest that, according to a predominance of adult and old individuals (from 48 to more than 96 months old) and mostly females, caprine livestock was primarily exploited to obtain secondary products, i.e. milk and wool. Furthermore, the increase in herd size may have been a further reason for requiring two different reproductive seasons. On this subject, according to Colominas (2013a), the rural establishment would have counted on a flock of approximately 60–80 individuals. Thus, the constant availability of a consistent number of

individuals to be either sacrificed or exploited during their lifetime or to be exchanged as trade products would have been ensured. Finally, birth synchronisation by herders enabled them to focus all of their efforts on monitoring lambing and taking care of the youngest animals at a given time (Balasse et al. 2020). This complex herding system also implies that, at Mas Castellar de Pontós, herders had to provide the adequate amount of pasture resources required to support autumn and winter lactation. During the Iberian-Roman period, warmer and/or moister conditions and a strong seasonality with frequent precipitations in the cold season characterised the whole Mediterranean basin, particularly in the north-western Mediterranean (González-Sampériz et al. 2017). Consequently, at Mas Castellar de Pontós, herders could offer a sufficient quantity of forage to sustain autumn and winter lactation, relying on favourable climatic conditions. Furthermore, the integration of fodder from cereal cultivation might be used to feed the herd. The presence of both winter and spring crops at the site would have allowed the availability of crop residues for a large period of time during the year, particularly during those seasonal times when pasture resources are at their lowest.

The environmental conditions and the economic necessities in Tossal de Baltarga were totally different. The high mountain settlement is located in a constrained environment, where the vegetation is completely covered by snow during winter. At the same time, the site was a control point of mountain routes. Therefore, the reproduction pattern documented here was in accordance with the livestock necessities of their inhabitants. The best strategy was hence to rely on natural births in late winter/spring, with a reduced duration to minimise the labour of caring for pregnant and newborns and to ensure their survival. It was not convenient for the Tossal de Baltarga inhabitants to have a prolonged lambing season or even less autumn births. The latter, indeed, would have forced newborns to face the harsh winter in the Pyrenees during their first months of life. On the other hand, late winter/spring births allowed the newborns to approach the cold winter temperatures with the right physical condition to get through it. Zooarchaeological studies show the presence of sheep from different ages at the site, from 2 to 6 months old to 4 years old, with a slight predominance of adult individuals (24–48 months old) and an absence of old individuals (more than 72 months old). These data suggest the preferential use of sheep as meat producers. Neither any bone belonging to perinatal, neonatal or infant individuals has been recovered that could correspond to deaths related to environmental conditions.

The data from Sant Esteve d'Olius and Turó de la Rovira, located in an inland region and on the coast respectively and with different specific functions (see 2. Sites), are more difficult to interpret. The isotopic data shows the presence of a single group of births, but with a longer lambing period

than the natural one. Is this choice the result of the demand for secondary products for a longer period of time, but not throughout the whole year? Or are we seeing a concrete moment within a breeding management system that is setting the stage for a “de-seasoning” of the herd in autumn? According to zooarchaeological data, sheep were mainly exploited in both settlements to obtain meat and, secondarily, wool and milk (Colominas 2013b, 2019). Therefore, secondary products had a significant economic role in both sites, but not as much as seen at Mas Castellar de Pontós. This may explain the requirement for a longer lambing period without the seasonal separation into two distinct groups. However, it is difficult to determine whether these prolonged lambings were planned within the agro-pastoral calendar or resulted from a “catch-up mating” setup due to low spring fertility (Balasse et al. 2023).

Conclusion

An insight into different sheep seasonal reproductive patterns adopted by the Middle/Late Iron Age societies in the north-eastern Iberian Peninsula is provided in this paper. Based on the results, a first and innovative glimpse into a complex and specialised livestock husbandry during the third century BC can be gained. Sequential oxygen isotope analyses in the second and third lower molars of sheep from four different sites reveal that sheep were generally able to give birth all year round. De-seasoning of the flock, however, was not practised systematically in every settlement; planning and management of sheep births were determined by economic purposes and environmental forces. As a result, the four sites studied here display different husbandry models: the demand for year-round availability of secondary products forced the co-presence of two different lambing periods at Mas Castellar de Pontós; at Tossal de Baltarga, the duration and the period of births was according to the economic necessities, and it also had to adapt to environmental restrictions; the cases of Sant Esteve d'Olius and Turó de la Rovira represent an in-between compared to the two previous models, with the possibility of manipulating the flock in both duration and period of births, but with no autumn lambing needed.

It is evident that, during the Iron Age, Iberian herders possessed excellent knowledge about sheep reproductive physiology and knew how to apply it according to the desired and sustainable type of exploitation. In order to be able to breed sheep at different times of the year, it was necessary to have a number of people dedicated exclusively and specifically to planning the management and exploitation of the herds, starting from the control of the reproductive calendar. This huge technical effort inevitably suggests that husbandry played a significant role in the economy of these

communities and was perfectly fitted into the agricultural schedule. Indeed, it must be kept in mind that agriculture, and specifically cereal production, has always been considered the main activity, thanks, fundamentally, to the archaeological evidence of silo fields. This study highlights how, during the third century BC, a considerable workforce, technical knowledge, time and resources were employed in livestock practices. The data provides evidence that sheep births were intentionally manipulated by herders in two distinct ways: on the season and on the duration of the lambing period. Therefore, oxygen isotope data combined with zooarchaeological information has allowed us to propose that animal husbandry also contributed significantly to the economy of these communities. It has also allowed documenting how communities controlled sheep reproduction in relation to the products they wanted to exploit. On the other hand, isotope analyses have demonstrated that distinct livestock breeding strategies were adopted by different communities in relation to their own environmental conditions, economic needs and political decisions. Extending the research to additional Iron Age Iberian settlements is required in order to address the new questions and insights that have emerged from the data gathered. Indeed, the study of several settlements with different functionalities and localised in different environments is necessary in order to define the husbandry practices, with all their nuances, that characterised Iberian societies and to search for possible economic, political and/or environmental patterns. This will allow us to know whether these different reproductive patterns and livestock management practices were part of one integrated system or reflect multiple and separated groups of herders. Finally, the results presented in this paper need to be complemented by further ongoing isotopic studies related to livestock diet and mobility; the huge amount of data obtained will allow a further and innovative immersion in the management and exploitation of sheep livestock by the Iberians. Therefore, it is clear that the potential of data acquired through the implementation of biogeochemical analyses in order to provide knowledge about protohistoric societies is enormous, and it is imperative to exploit it.

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Author contribution C.M. wrote the main manuscript, prepared figures and proceed the data. C.T. and L.C. reviewed the manuscript.

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4.2 Mobility strategies

The following section addresses the second research objective of the thesis, focusing on the sheep mobility strategies (pastoral strategies) employed by the Iberian communities from present-day Catalonia during the Middle and Late Iron Age. Limited information is available on the potential mobile herding systems adopted by Iberian societies, whether at short or long distances, including altitudinal mobility patterns. Therefore, this study provides novel and fundamental data on livestock mobility, and altitudinal mobility in particular, for this chronology through the combination of multiple isotopic proxies: $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$. The outcomes of this study are published in the article titled “Between valleys, plateaus, and mountains: unveiling livestock altitudinal mobility in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope approach”.

4.2.1 Paper 2. Between valleys, plateaus, and mountains: unveiling livestock altitudinal mobility in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope approach

This paper reports for the first time evidence of migrations between different altitudinal and geological areas during the Iron Age. The four settlements exhibit four distinct husbandry models, highlighting the extraordinary adaptability of the Iron Age Iberian populations in mobile livestock strategies before the acquisition of the zootechnical improvements introduced by the Romans. Furthermore, the results depict the Iberian societies of the 3rd century B.C. as being connected through a strong network of social and economic relations that should support

the mobile livestock system. However, sheep mobility was not widespread and was only practised when deemed necessary and/or profitable.

This study also provides the first evidence of seasonal altitudinal movements between the Pyrenees and the lowlands. These data therefore pave the way for the image of a more integrated and connected Ibero-Pyrenean world with its contemporary lowland communities. In addition to its historical relevance, this research also showcases the effectiveness of integrating data obtained from the sequential analysis of carbon and oxygen values with those derived from strontium analysis. These results highlight the importance and necessity of an integrated multi-isotope analysis approach to effectively trace herd movements along different altitudinal and geological areas.



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EDITED BY

Canan Cakirlar,
University of Groningen, Netherlands

REVIEWED BY

David Kaniewski,
Université Toulouse III - Paul Sabatier, France
David Meiggs,
Rochester Institute of Technology (RIT),
United States

*CORRESPONDENCE

Chiara Messina
✉ cmessana@iphes.cat
Carlos Tornero
✉ Carlos.Tornero@uab.cat

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Between valleys, plateaus, and mountains: unveiling livestock altitudinal mobility in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope approach

Chiara Messina^{1,2*}, Carlos Tornero^{1,3*}, Richard Madgwick⁴,
Angela L. Lamb⁵, Jane Evans⁵ and Lúcia Colominas⁶

¹Institut Català de Paleoeologia Humana i Evolució Social (IPHES-CERCA), Tarragona, Spain,

²Departament d'Història i Història de l'Art, Universitat Rovira i Virgili (URV), Tarragona, Spain,

³Department of Prehistory, Autonomous University of Barcelona (UAB), Bellaterra, Spain, ⁴School of History, Archaeology and Religion, Cardiff University, Cardiff, United Kingdom, ⁵National Environmental Isotope Facility (NEIF), British Geological Survey, Nottingham, United Kingdom, ⁶Institut Català d'Arqueologia Clàssica (ICAC-CERCA), Tarragona, Spain

Seasonal altitudinal mobility has been a key practice among pastoral societies in the north-eastern Iberian Peninsula to cope with the unpredictable Mediterranean climate. The existence of a massive and regulated mobile herding system in this area dates back to the 12th century. Nevertheless, early herd connections between the lowlands and the Pyrenees during the Roman period have been documented. The available information regarding the potential adoption of sheep's mobile pastoralism by Iberian societies prior to the Romans' arrival is limited. This study aims to provide fundamental new insights into livestock altitudinal mobility during this period through a biogeochemical approach. Sequential analysis of carbon and oxygen isotope values is combined with strontium isotope ratios from sheep second and third lower molars from four Catalan sites (Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, Turó de la Rovira). The results reveal evidence of migrations across different altitudinal and geological areas, unveiling the great adaptability of mobile livestock strategies by Iberian populations. The first evidence of descending herds' mobility from the Pyrenees to the lowlands prior to the Roman conquest is also attested. Finally, the effectiveness of multi-isotope analysis ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$) in detecting seasonal livestock movements is demonstrated. Thus, this study provides a comprehensive and nuanced understanding of the complexity of sheep livestock management of the north-eastern Iberian societies during the Middle/Late Iron Age. Moreover, the research points to a more integrated and connected Ibero-Pyrenean world with contemporary lowland communities than so far suggested. However, animal mobility was not widely practised and was possibly determined by the environmental conditions, economic needs, and political decisions of each settlement.

KEYWORDS

seasonal livestock mobility, stable isotopes, carbon and oxygen, strontium, Middle/Late Iron Age, NE Iberian Peninsula, animal husbandry strategy

1. Introduction

Seasonal altitudinal mobility has always been one of the main practices adopted by Mediterranean pastoral societies to cope with the unpredictable and highly variable climatic conditions (Gómez-Pantoja, 2004; Oteros-Rozas et al., 2013). The Mediterranean climate is, in fact, distinguished by marked seasonal fluctuations in pasture availability and rainfall, as well as the contrast between arid lowlands in the summer and snow-covered highlands during the winter (Davies, 1941; Georgoudi, 1974; Ruiz and Ruiz, 1986). Consequently, the seasonal altitudinal migration of herds allows the complementary exploitation of both fresh highland pastures during the summer and warmer lowland ones during the winter (Davies, 1941; Gómez-Ibañez, 1977; Cleary, 1986; Ruiz and Ruiz, 1986). This correspondence between the herd's fodder requirements and the seasonal peaks in pasture availability ensures optimal feeding of the animals throughout the year (Ruiz and Ruiz, 1986; Manzano-Baena and Casas, 2010; Oteros-Rozas et al., 2013). Seasonal altitudinal mobility is a livestock strategy particularly suited to the ecological and orographic conditions of the Iberian Peninsula. Indeed, a year-round complementarity between lowland and highland areas is favoured by the presence of large areas with a Mediterranean climate (Ruiz and Ruiz, 1986; Gómez-Pantoja, 2004; Manzano-Baena and Casas, 2010). In the Iberian Peninsula, mobile pastoralism has historically been mainly related to sheep husbandry and fine wool production (Blanks, 1995; Manzano-Baena and Casas, 2010; Nieto Espinet, 2016; Tornero et al., 2018). This husbandry strategy reached its peak during the Middle Ages, with the official formation of the *Honrado Concejo de la Mesta* in 1273, the most prominent example of a herder organization in the Mediterranean. This powerful and wealthy syndicate supervised the seasonal altitudinal migration of thousands of herds between the Segovia highlands and the vast southern lowlands (Brun, 1996; Gómez-Pantoja, 2004; Oteros-Rozas et al., 2012). In the north-east of the Iberian Peninsula (present-day Catalonia), the organization of a large-scale seasonal altitudinal migration system of herds has medieval origins (11th–12th c.), developed by Pyrenean rural communities and major monasteries. The latter renovated the existing route network that spanned the entire territory, connecting plains, Pre-Pyrenees, and Pyrenees (Vilà i Valentí, 1991; Martí et al., 1995). This extensive network of routes follows the traces of ancient pathways, reinforced by the Roman road and bridge system (Ruiz and Ruiz, 1986; Alfaro, 2001). Indeed, under the Romans, a long-distance trade network was consolidated in the eastern Pyrenees. These trade routes were also used by the mobile flock and were not only to connect the different grazing areas, but also to maintain them under tributary control (Olesti, 2022). Although there is no direct evidence of structured seasonal altitudinal mobility during Roman times, it seems unlikely that such a profitable and widespread activity in Italy was not also practised in provinces with suitable climatic conditions, available land for livestock pasturing, and flocks (Gómez-Pantoja, 2001). Indeed, the first direct attestation of mobile pastoralism coincides with the first legal regulation of these pastoral routes with the *Fuero Juzgo*, the Visigothic code of laws, between the 6th and 7th centuries. This text includes regulations for the passage of livestock through open fields and public roads. This code of laws was

compiled from prior Roman common law, suggesting the existence of a regulated and organized livestock seasonal mobility under Roman rule (Ruiz and Ruiz, 1986; Gómez-Pantoja, 2001, 2004; Euba, 2008; Manzano-Baena and Casas, 2010). Colominas et al. (2019) applied geometric morphometrics to the study of size and shape variability in sheep astragali from nine sites dated from the Middle Iron Age to the Early Roman period (5th century BC–3rd century AD) and located in the eastern Pyrenees (Cerdanya) and the north-eastern Iberian coast (Empordà plain). The results obtained were combined with data-sets from Number of Identified Specimens (NISP) and slaughtering patterns from traditional zooarchaeological studies. According to Colominas et al., data from the Roman period reveal that both mountainous and coastal sites exhibited similar astragali size and morphology, as well as the implementation of similar husbandry practices. This evidence would suggest the existence of a connection between the two areas, involving a shared orientation in the exploitation of sheep and possible seasonal altitudinal movements of the herds. On the other hand, during the Middle Iron Age, there was a clear distinction in size and husbandry strategies between the herds raised in the mountain sites and those bred by the Iberian communities in the lowland coast. The local character of the livestock practices and the presence of different sheep populations between the two areas during this period would suggest few livestock connections between mountain and coastal communities. Therefore, a regular livestock mobility from the lowland coast to the Pyrenees and vice versa would have occurred for the first time during the Roman period. Indeed, under Roman rule, increasing anthropogenic pressure on the local landscape would have made the migration of livestock to ecologically complementary areas necessary for their feeding (Nolla et al., 2010; Colominas et al., 2019). In two previous studies, Valenzuela-Lamas et al. (2016, 2018) carried out strontium isotopic analyses on sheep and goat teeth from the site of Turó de la Font de la Canya (Barcelona), dated between the 7th and 2nd centuries BC. The obtained strontium values are quite homogeneous and do not show any evidence of long-distance seasonal mobility, suggesting that Iron Age communities in the north-eastern Iberian Peninsula practised limited-scale husbandry.

From the Middle Iron Age until the Roman conquest, these communities were characterized by a proto-state structure. This strongly hierarchical system was organized into several centralized political entities (Gracia, 2005; Sanmartí, 2014, 2021). Within this framework, a wide array of interconnected open-air settlements with specific functions emerged: i.e., fortified centers, rural establishments, small villages, and silo fields (Gracia, 2005; Sanmartí, 2014, 2021). All these settlements were structured around the so-called first-order cities, which operated as central nuclei responsible for the control and centralization of agricultural production (Asensio et al., 1998; Bouso et al., 2000; Sanmartí, 2004, 2014; Sanmartí et al., 2019). These communities developed a predominantly agricultural economy devoted to self-sufficiency, with cereal surplus being the main exchange product (Asensio et al., 2003a; Asensio, 2013; Prats et al., 2020). Animal husbandry played a significant role and was perfectly suited to the agricultural schedule (Messana et al., 2023). It was mostly specialized in caprines, with a predominance of sheep, and counted on diversified and selective livestock strategies,

catered to the necessities of each settlement (Albizuri and Nadal, 1999; Franquesa et al., 2000; Colominas, 2008, 2013; Colominas et al., 2019; Nieto Espinet et al., 2021). Previous oxygen isotope analyses have also documented that distinct breeding strategies were adopted by different Iberian communities in relation to their environmental conditions, economic needs, and political decisions (Messana et al., 2023). Sheep husbandry was, therefore, a key activity among the subsistence strategies of Iron Age communities in the north-eastern peninsula. However, there is limited information available regarding the potential mobile herding systems at short or long distances adopted by Iberian societies. To address this lacuna, in this study we apply a biogeochemical approach (isotope analysis) to investigate seasonal altitudinal mobility of herds in four Middle/Late Iron Age settlements located in the north-east of the Iberian Peninsula: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira. Different isotopic signatures retrieved from sampled sheep individuals to trace signs of livestock mobility: sequential dental series of carbon, oxygen, and strontium analysis. These data not only offer crucial information on livestock management by Iberian communities before Roman conquest but also provide important evidence about the nature of the relationships between them.

Mobile pastoralism can be challenging to detect archaeologically because it leaves highly ephemeral traces. Stable isotope analyses have emerged as a fundamental tool for addressing this issue and allowing a characterization of husbandry strategies, including the seasonal altitudinal mobility of livestock. Indeed, the isotopic signatures incorporated into sheep molar enamel from the food and drinking water they consumed can be used to reconstruct the environmental conditions in which the animals lived and how these changed during their lives (Balasse and Ambrose, 2005; Tornero et al., 2018). Following this principle, livestock mobility can be detected by, but not only, the inverse relationship between oxygen and carbon values ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, see Section 2.3.1.) along the sequential dental series, as originally proposed in Tornero et al. (2016, 2018).

In the sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, seasonal altitudinal movements of a sheep herd between pastures with different vegetation and meteoric waters are identified along the intra-tooth dental series when high $\delta^{13}\text{C}$ values coincide with low $\delta^{18}\text{O}$ values and vice versa (Makarewicz et al., 2017; Knockaert et al., 2018; Janzen et al., 2020; Tejedor-Rodríguez et al., 2021). Tooth enamel does not remodel once mineralized and, as a result, reflects the isotopic signatures registered during its formation. The oxygen isotope composition of enamel mineral fraction (i.e., bioapatite compound) is primarily derived from ingested water and plant consumption (Longinelli, 1984; Luz et al., 1984). These isotopic signatures are related to the meteoric water and temperature, which vary seasonally in temperate latitudes. At mid and high latitudes, higher $\delta^{18}\text{O}$ values are indicative of the warmer season, whilst lower $\delta^{18}\text{O}$ values occur during the coldest one (Gat, 1980). $\delta^{13}\text{C}$ values measured in bioapatite are related to the carbon isotopic composition of the plants that were consumed (Lee-Thorp and Van der Merwe, 1987). This mainly varies according to plants' photosynthetic pathway (i.e., C_3 and C_4), but it can also be influenced by growing conditions and other factors (Bender,

1971; Farquhar et al., 1989). Vegetation in Western Europe is generally dominated by C_3 plants, which are typical of temperate environments, while wild C_4 plants are inexistent or residual, and if present, always located in lowland areas (Mateu, 1992; Tafuri et al., 2009; Pyankov et al., 2010). Generally, C_3 plants grown in dry environments tend to have higher $\delta^{13}\text{C}$ values than those adapted to humid conditions. This is due to their greater water use efficiency. Conversely, plants grown in humid environments show lower $\delta^{13}\text{C}$ values (Farquhar et al., 1989; Friend et al., 1989; Körner et al., 1991; Kohn, 2010). Furthermore, $\delta^{13}\text{C}$ values slightly increase along altitudinal gradients due to the decrease in CO_2 pressure on $\delta^{13}\text{C}$ (Körner et al., 1991). In addition, seasonality has a moderate influence on the $\delta^{13}\text{C}$ values of C_3 plants. Consequently, the highest values occur during the warmest and driest season, whereas the lowest values are observed during the coldest and wettest season (Smedley et al., 1991; Diefendorf et al., 2010; Hartman and Danin, 2010). Based on these premises, the negative co-variation of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences along the tooth crown provides evidence for seasonal altitudinal mobility of livestock between pastures with distinct meteoric waters and vegetation. In this way, individuals grazing at higher altitudes during the summer months return a sequence with the highest $\delta^{13}\text{C}$ values corresponding to the lowest $\delta^{18}\text{O}$ values. By contrast, individuals grazing at lower altitudes during the winter months show a sequence with the lowest $\delta^{13}\text{C}$ values corresponding to the highest $\delta^{18}\text{O}$ values. In this study, the modern references presented in the works of Knockaert et al. (2018) and Tornero et al. (2018) are used as baselines for interpreting the archaeological data. Both of these cited studies were conducted in the Pyrenees Mountains, the closest elevated locations to the archaeological sites where samples were recovered. These are the only two available experimental studies in the study region.

Strontium isotope ratios can provide evidence of mobility between territories with different geological substrates. This is because the geochemical signature of strontium isotopes is directly related to the geology of the area where an animal acquires food. Radioactive rubidium (^{87}Rb) decays into ^{87}Sr over time and, consequently, the $^{87}\text{Sr}/^{86}\text{Sr}$ values in rock minerals vary depending on their original Rb/Sr content and geological age (Ericson, 1985; Beard and Johnson, 2000; Price et al., 2002). $^{87}\text{Sr}/^{86}\text{Sr}$ 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 (Ericson, 1985; Beard and Johnson, 2000; 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; Price et al., 2002; Madgwick et al., 2012). As a result, possible herd movement during the developmental period between two locations with a measurable strontium isotope difference can be traced (Montgomery, 2010).

In this study, for the first time, the seasonal altitudinal mobility of sheep herds in the Iberian Peninsula during protohistoric periods is investigated by examining the relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values on sampled dental series of individuals analyzed. Additionally, we integrated $^{87}\text{Sr}/^{86}\text{Sr}$ measurements in the same dental series to explore the movements across different altitudinal and geological areas in more detail and test the effectiveness of

combining these proxies. This approach has been successfully applied before (Balasse et al., 2002; Bentley and Knipper, 2005; Meiggs, 2009; Viner et al., 2010), especially in contexts where complex orogenic areas are absent. Moreover, relying on the results of $^{87}\text{Sr}/^{86}\text{Sr}$ analyses makes it possible to determine the cause of the increase in $\delta^{13}\text{C}$ values in an individual during winter. This, in fact, may be produced either by a change in the pasture as a result of an altitudinal movement or by the integration of C_4 plants into the diet. The presence of domesticated C_4 plants such as millet (*Panicum milliaceum*) and foxtail millet (*Setaria italica*) is attested in almost all the settlements here studied (Canal, 2000, 2002; Riera et al., 2020; Colominas et al., in press). Consequently, their eventual use as livestock fodder during winter would overshadow the seasonal mobility signals displayed by the inverse relationship between the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sequences. Substantial variations in $^{87}\text{Sr}/^{86}\text{Sr}$ are explored at an intra-individual level in correspondence with the inverse relationship of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences. These variations serve as evidence of a change in pasturage, indicating in-life mobility. Establishing allochthonous origins and evidence for mobility is the principal objective, rather than identifying origins. Determining origins is a complex task and would require substantial $^{87}\text{Sr}/^{86}\text{Sr}$ biosphere mapping work in this area, especially given its relative lithological complexity. However, two of the four selected sites for this study, Mas Castellar de Pontós and Sant Esteve d'Olius, are situated in geologically homogeneous zones (Solsonès and Empordà), which may facilitate the interpretation of strontium isotope data at these specific locations.

2. Material and methods

2.1. Archaeological sites and geological settings

The sheep molars selected for this study derive from four extensively studied sites with contemporary and well-dated occupations in the 3rd century BC. No major vegetation changes have been documented in the north-east of the Iberian Peninsula during this period (Burjachs et al., 2000). The four settlements are located in distinct ecological and cultural areas of present-day Catalonia, within Cenozoic sedimentary basins (Voerkelius et al., 2010; Institut Cartogràfic i Geològic de Catalunya, 2023). The latter are formed from the erosive products of earlier terrains. The four sites are open-air settlements situated along three of the main and oldest traditional pastoral routes that converge in the eastern Pyrenees (Figure 1). For this reason, they are particularly well suited to evidence herd movements from winter pastures in the lowlands to summer pastures in the highlands.

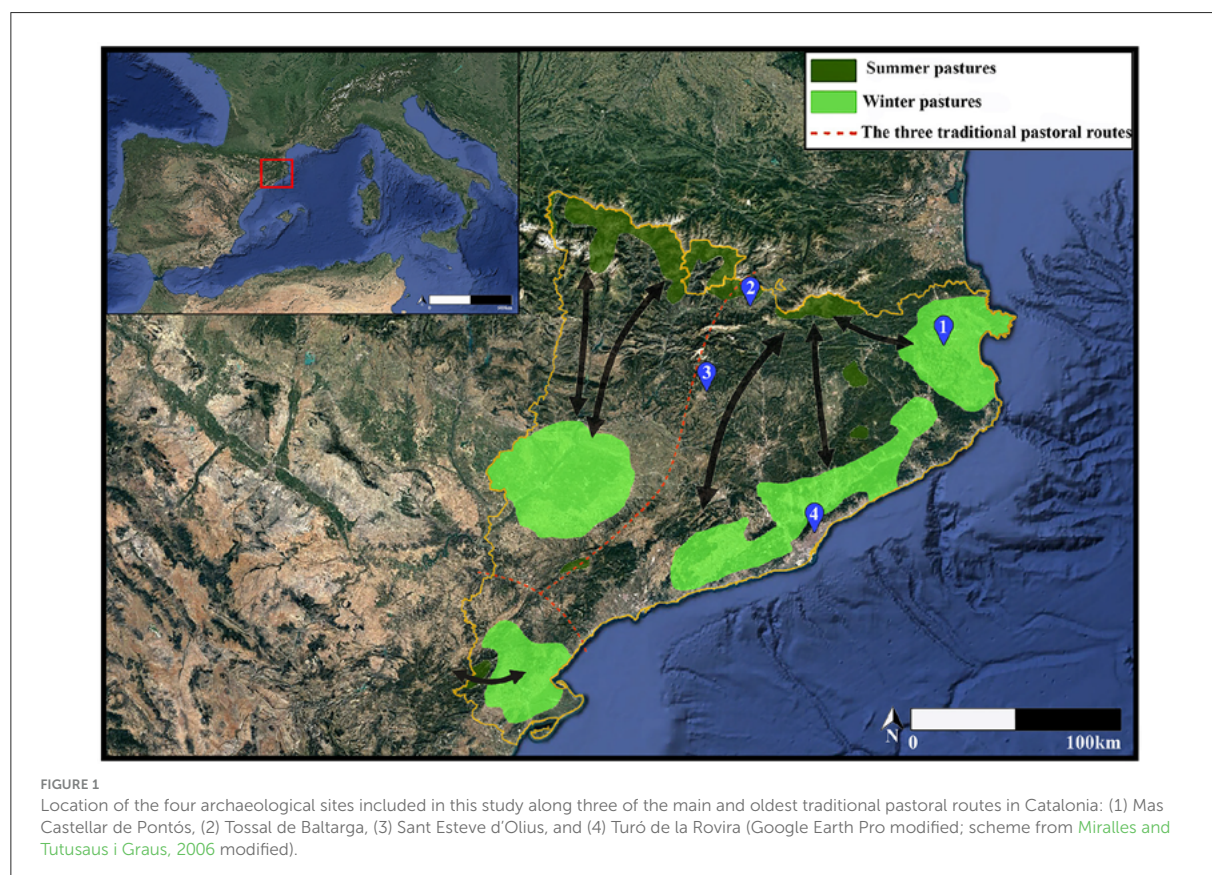
Mas Castellar de Pontós is situated in the Empordà region (Girona, maximum altitude: 154 m a.s.l.; Figure 2), a vast and fertile plain in the northern pre-coastal area, in the territory of the Indigeti. It is located approximately 17 km equidistance from the Greek colonies of *Rhode* and *Emporion*. The site is founded on Miocene and Pliocene conglomerates, with sandstones and shales (Institut Cartogràfic i Geològic de Catalunya, 2023). Based on analogous lithologies from the UK, the geological formation of the

area suggests that individuals grazing locally would likely exhibit strontium values close to 0.7092 (Evans et al., 2010). Mas Castellar de Pontós was occupied during a wide chronological frame, ranging from the late 7th century to the early 2nd century B.C. (Adroher and Pons, 2002; Pons et al., 2010). Between 250 and 180 B.C. it was occupied as a specialized agricultural settlement, with an associated extensive silo field (Pons et al., 2010). Under the governance of a rural aristocracy, Mas Castellar de Pontós played a crucial role as a commercial enclave for cereal production and served as a major reserve center for the entire Emporion area (Bouso et al., 2000; Fuertes et al., 2002). The sheep remains analyzed were recovered from one of the houses and from two silos.

Tossal de Baltarga (Bellver de Cerdanya, 1166 m a.s.l.; Figure 2) is a high mountain Ceretan settlement in the eastern Catalan Pyrenees. The area is mainly dominated by Devonian limestones (Institut Cartogràfic i Geològic de Catalunya, 2023), which are expected to display a strontium signature ranging between 0.708 and 0.709 (Evans et al., 2010). The primary purpose of the settlement was to exercise territorial control over the communication routes that crossed this area. Chronologically, the site has revealed three different phases ranging from the Late Bronze Age to the Republican Roman period (Morera, 2017). During the Iberian phase (4th–3rd century BC), the settlement featured several residential and working buildings (Morera, 2017; Colominas et al., in press). The site, which had a certain social and economic relevance within the Ceretan population, was destroyed by fire toward the end of the 3rd century BC (Morera, 2017). Consequently, the individuals studied here are contemporary, victims of the same violent event. Preliminary results of micromorphological analyses carried out on soils from one of the buildings reveal the presence of an organic-rich deposit, primarily composed of herbivore dung. While these results do not provide information on herd mobility, the study is valuable for reconstructing both the spatial organization within the building and the dietary regimes of the animal stabled there (Colominas et al., in press).

Sant Esteve d'Olius (Solsonès, 664 m a.s.l.; Figure 2) is a village in the Pre-Pyrenees area, in the fertile Lacetan plain. It occupies the highest point of a small promontory, bordered by the river Cardener, the main communication link with the coast (Asensio et al., 2003b). Geologically, the site comprises Oligocene marls, limestones, and sandstones (Institut Cartogràfic i Geològic de Catalunya, 2023). The presence of marls, and thus carbonate, suggests strontium values around 0.709 (Evans et al., 2010). During the Iberian phase (3rd century BC), the settlement was fortified and specialized in the storage and management of cereal surpluses, with silo fields and residential buildings (Asensio et al., 2003b; Chorén and Caldach, 2006; López, 2009). The sheep molars analyzed in this study were collected from seven distinct silos.

The Laietan site of Turó de la Rovira (mid-3rd century BC - late 3rd/early 2nd century BC) is located near the central Mediterranean coast. It is a fortified settlement situated on top of the homonymous plain in Barcelona (Barcelonès, 262 m a.s.l.; Figure 2; Colominas i Roca, 1954; Giner, 2018). The settlement lies on a complex and patchy area characterized by Silurian-Danovan nodular limestones and sericitic slates, and Silurian amplitic slates, phyllites and sericites (Institut Cartogràfic i Geològic de Catalunya,



2023). These older rock formations can display a range of strontium values between 0.711 and 0.713, suggesting the potential for higher local biosphere values compared to the other three sites (Evans et al., 2010). Bounded by a wall, the site features a moat on the south-eastern side, two silo fields concentrated on both sides of the village, and residential buildings on the southern slope (Giner, 2018). The settlement occupied a dominant position over the surrounding minor centers (Giner, 2018). Sheep remains come from silos with similar chronology and whose content of archaeocarpological remains is homogeneous (Riera et al., 2020).

2.2. Materials

A total of 31 lower molars (18 second molars and 13 third molars) belonging to 22 sheep (*Ovis aries* Linnaeus, 1758) were selected for sequential oxygen and carbon isotope analyses; among these, 12 teeth (seven second molars and five third molars) from seven individuals were chosen for strontium isotope analysis. Ten second molars and seven third molars were recovered from mandibles, while the remaining were isolated teeth. All molars show entirely or almost fully formed crowns and early wear stages. The results of sequential oxygen and carbon isotope analyses of three second molars (BTB 3249, BTB 3270, BTB 3271) and one third molar (BTB 3270) here included were previously used for a study about the Tossal de Baltarga site (Colominas et al., in press). Table 1 provides descriptive information (side, wear stage,

estimated age of death, and type of analysis) about the teeth analyzed for this study.

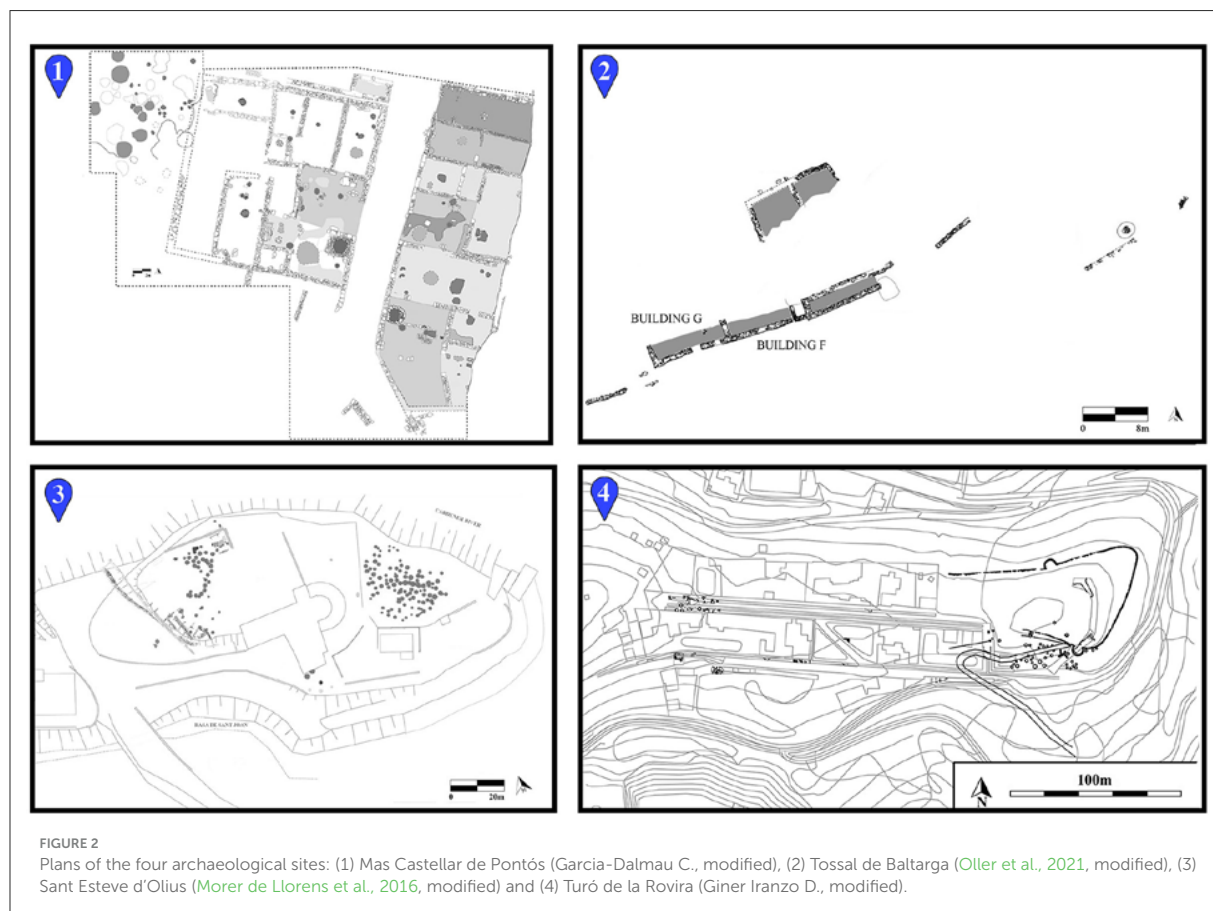
2.3. Methods

2.3.1. Sequential oxygen and carbon isotope analyses

Following the cleaning of the selected teeth's surface by abrasion with a tungsten drill, enamel bands were sequentially sampled using a diamond bit. Sampling was performed on the distal lobe of M_2 and the central lobe of M_3 , always on the buccal surface. All specimens were progressively taken at 1–2 mm intervals along the whole crown height, from the apex to the enamel root junction (ERJ); starting from the latter, the positions of the samples-bands were measured.

A total of 473 powdered enamel samples (weighing between 2.5 and 13.7 mg) were drilled and chemically treated at the Biomolecular Laboratory of the Institut Català de Paleoeologia Humana i Evolució Social (IPHES-CERCA), following the protocol described in Balasse et al. (2002) and modified by Tornero et al. (2013). In order to eliminate contamination from exogenous carbonates, samples were pre-treated for 4 h in 0.1 M acetic acid [CH_3COOH] (0.1 ml solution/mg of sample), rinsed five times in distilled water and dried in an oven at 70°C for 48 h.

Pre-treated samples weighting ~600 µg were measured using an automated carbonate preparation device (KIEL-III) interfaced



to a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Dept. of Geosciences), University of Arizona (USA), with scientific supervision from Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. The accuracy and precision of measurements were checked and calibrated using NBS-19 and NBS-18 international standards. A mean analytical precision within each run and from replicate measurements of standards during analysis was $\pm 0.10\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.08\text{‰}$ for $\delta^{13}\text{C}$ (1σ). Isotope composition is reported in δ notation and expressed per mil (‰), stating the deviation of the isotope ratio from the V-PDB (Vienna-Pee Dee Belemnite) standard for both carbon and oxygen values (McKinney et al., 1950; Gross, 2017).

2.3.2. Strontium isotope analysis

Twelve teeth from seven individuals were sampled for strontium isotope analyses (selected teeth are reported in Table 1). To assess the compatibility and effectiveness of the two combined methods, samples were collected from three individuals whose molars exhibit altitudinal mobility according to their $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, as well as from four sedentary individuals. Sampling for strontium isotope analysis was performed close to the point of maximum and minimum events record in the oxygen series.

Enamel samples were treated at the British Geological Survey-BGS (UK), with technical support from Doris Wagner. After cleaning each tooth surface using a tungsten carbide dental bur, an enamel sample was cut using a flexible diamond edged rotary dental saw. Sampling was performed on the buccal side, on the anterior lobe of M_2 and M_3 , except in two cases (TR M2 831, TR M2 725) on the distal lobe of M_2 , on the lingual surface and in one case (TR M3 725) on the central lobe of M_3 , on the lingual side. A minimum of one and a maximum of three samples per tooth were cut. All sample surfaces were mechanically cleaned with a diamond bur to remove adhering dentine. The resulting sample was transferred to a clean (class 100, laminar flow) working area for further preparation. The sample was first cleaned ultrasonically in high purity water to remove dust, rinsed twice, and then soaked for an hour at 60°C, rinsed twice, then dried and weighed into pre-cleaned Teflon beakers. The sample was mixed with ^{84}Sr tracer solution and dissolved in Teflon distilled 8M HNO_3 and converted to chloride form using 6M HCl . Strontium was collected using Eichrom AG50 X8 resin columns. Strontium was loaded onto a single Re Filament following the method of Birck (1986) and the isotope composition and strontium concentrations were determined by Thermal Ionization Mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer. The international standard for $^{87}\text{Sr}/^{86}\text{Sr}$, NBS987,

TABLE 1 Sampled specimens (ID) from the four archaeological sites included in this study: Mas Castellar de Pontós (MC), Tossal de Baltarga (BTB), Sant Esteve d'Olius (O), and Turó de la Rovira (TR); side (L, left; R, right), wear stages and estimated age of death according to [Payne \(1973\)](#); na, not analysed.

Teeth ID	Side	M ₂		M ₃	
		Wear stage	Age estimation	Wear stage	Age estimation
MC 11144	L	F	2–6 years	na	na
MC 12023	L	E	2–3 years	na	na
MC 20102	L	E	2–3 years	na	na
MC 20160*	R	E	2–3 years	F	3–4 years
MC 20165	R	F	3–4 years	F	3–4 years
MC 11132	R	na	na	G	4–6 years
MC 11134	L	na	na	G	4–6 years
MC 11138	L	na	na	G	4–6 years
BTB 3249	R	E	2–3 years	na	na
BTB 3270*	R	F	3–4 years	F	3–4 years
BTB 3271	L	D	21–24 months	na	na
BTB 3031	L	na	na	F	3–4 years
O 174*	L	E	2–3 years	na	na
O 205*	R	E	2–3 years	E	2–3 years
O 318	R	G	4–5 years	G	4–5 years
O 348	R	F	4–6 years	na	na
O 478	L	E	2–3 years	E	2–3 years
O 482	R	F	4–6 years	na	na
O 484*	R	F	4–6 years	na	na
TR 725*	R	F	3–4 years	F	3–4 years
TR 763	L	F	3–4 years	F	3–4 years
TR 831*	L	E	2–3 years	E	2–3 years

The asterisk mark (*) indicates the molars sampled for strontium isotope analysis.

gave a value of 0.710258 ± 0.000020 (2SD, $n = 8$) during the analysis of these samples. This is within uncertainty of the accepted value of 0.710250 and hence the data are uncorrected relative to the standard. The procedural blanks were between 40–80 picograms (pg).

3. Results

3.1. Oxygen and carbon isotope values

Results of the intra-tooth sequences of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are summarized in [Table 2](#) and fully presented in [Figure 3](#) and [Supplementary Table 1](#). The $\delta^{18}\text{O}$ values from all samples range from 2.6‰ to −4.6‰, with a mean of 0.4 ± 1.6 ‰ (1SD); the $\delta^{13}\text{C}$ values from all samples range from −6.9‰ to −13.9‰, with a mean of -11.3 ± 1.0 ‰. Mean $\delta^{18}\text{O}$ value within each specimen varies from 1.6‰ to −2.9‰, maximum values range from 2.6‰ to −1‰, and minimum values range from 1.0‰ to −4.6‰; mean $\delta^{13}\text{C}$ value within each specimen varies from −10.5‰ to −13.0‰, maximum values range from −6.9‰ to −12.3‰, and minimum values range from −11.3‰ to −13.9‰.

3.2. Oxygen and carbon isotope sequential series

All $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequential series are presented in [Supplementary Figure 1](#).

At Mas Castellar de Pontós, both the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences exhibit great intra-tooth variation, with a sinusoidal pattern and clear maximum and minimum events, reflecting the seasonal cycle. The oxygen sequence of individual MC 20102/s second molar represents the only exception, showing a narrow amplitude. The carbon sequence, on the other hand, appears in line with the others. All individuals show parallel $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences, with a positive correlation.

In general, all $\delta^{18}\text{O}$ sequences from Tossal de Baltarga, which exhibit the lowest values among those recorded in this study ([Figure 3](#)), show a sinusoidal pattern with clear maximum and minimum events and high intra-tooth variation along the crown. On the other hand, $\delta^{13}\text{C}$ sequences show low intra-tooth variation. The only exception is individual BTB 3270, whose oxygen sequence is incomplete due to wear and cannot reflect a full seasonal sequence. Instead, the carbon isotope sequence shows an increase

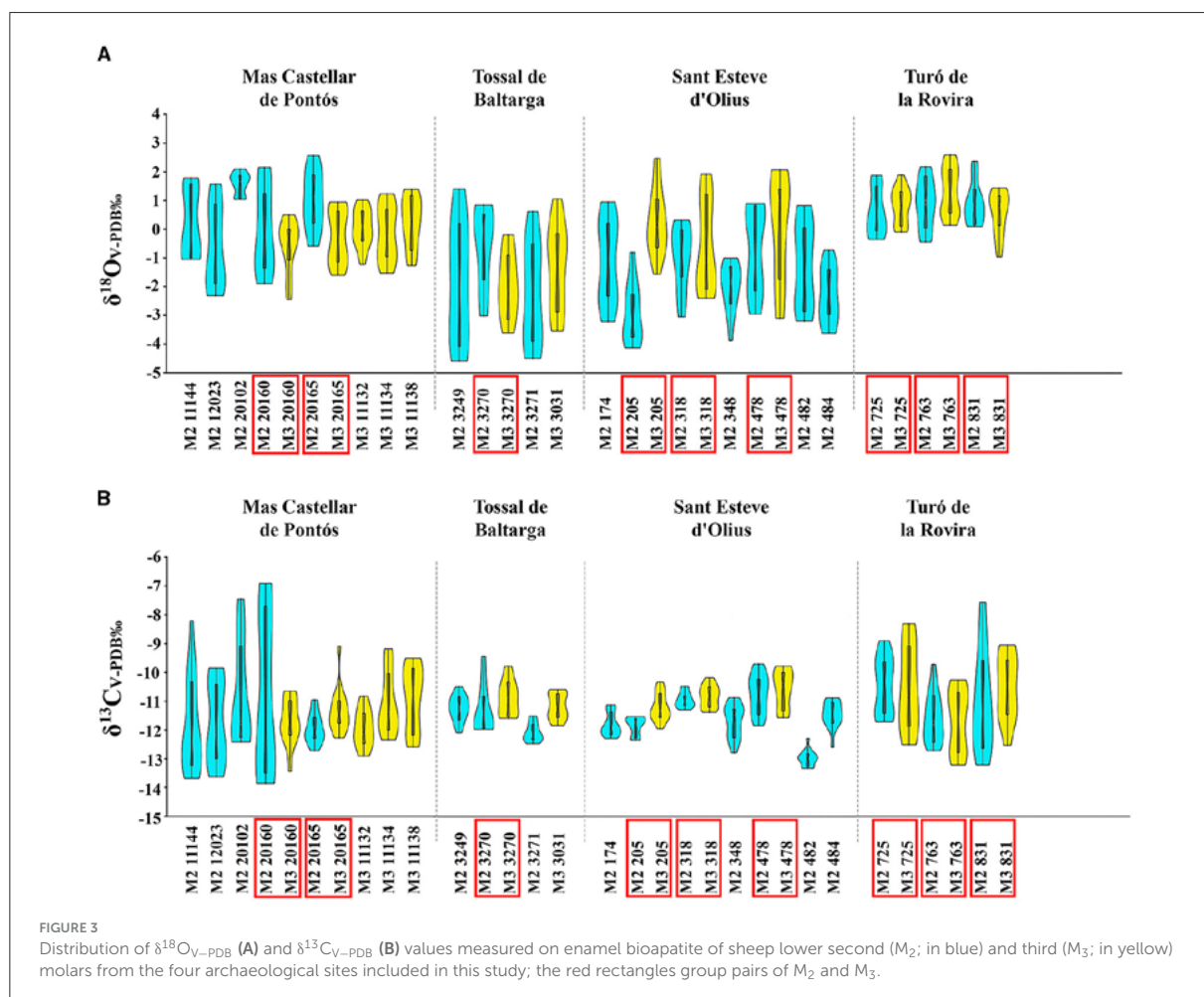
TABLE 2 Summarized $\delta^{18}\text{O}_{\text{V-PDB}}$ and $\delta^{13}\text{C}_{\text{V-PDB}}$ values measured on bioapatite samples from the lower second (M_2) and third (M_3) archaeological sheep molars: mean, range, maximum (max), and minimum (min) isotopic values.

Teeth	n	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$				$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$			
		Mean	Range	Max.	Min.	Mean	Range	Max.	Min.
MC M2 11144	16	0.2	2.8	1.8	−1.0	−11.8	−5.5	−8.2	−13.7
MC M2 12023	19	−0.6	3.9	1.6	−2.3	−11.8	−3.8	−9.8	−13.6
MC M2 20102	14	1.6	1.1	2.1	1.0	−10.8	−5.0	−7.5	−12.4
MC M2 20160	13	0.0	4.1	2.2	−1.9	−10.9	−7.0	−6.9	−13.9
MC M2 20165	14	1.0	3.2	2.6	−0.6	−11.9	−1.8	−11.0	−12.7
MC M3 11132	14	0.0	2.3	1.0	−1.2	−11.9	−2.1	−10.8	−12.9
MC M3 11134	13	−0.1	2.8	1.2	−1.5	−11.1	−3.2	−9.2	−12.3
MC M3 11138	17	0.2	2.7	1.4	−1.3	−10.9	−3.1	−9.5	−12.6
MC M3 20160	15	−0.6	2.9	0.5	−2.4	−11.7	−2.8	−10.6	−13.4
MC M3 20165	15	−0.3	2.6	0.9	−1.6	−11.3	−3.2	−9.1	−12.3
BTB M2 3249	16	−1.8	6.0	1.4	−4.6	−11.2	−1.6	−10.5	−12.1
BTB M2 3270	10	−0.6	3.9	0.9	−3.0	−11.3	−2.5	−9.4	−12.0
BTB M2 3271	13	−2.2	5.1	0.6	−4.5	−12.1	−1.0	−11.5	−12.5
BTB M3 3031	16	−1.3	4.6	1.1	−3.5	−11.2	−1.3	−10.6	−11.8
BTB M3 3270	12	−2.0	7.0	3.4	−3.6	−10.9	−1.8	−9.8	−11.6
O M2 174	18	−1.1	4.2	1.0	−3.2	−11.8	−1.2	−11.1	−12.3
O M2 205	15	−2.9	3.3	−0.8	−4.1	−11.9	−0.8	−11.5	−12.3
O M2 318	13	−1.0	3.4	0.3	−3.0	−10.9	−0.8	−10.5	−11.3
O M2 348	15	−2.0	2.9	−1.0	−3.9	−11.7	−1.9	−10.9	−12.8
O M2 478	16	−0.8	3.9	0.9	−3.0	−10.7	−2.1	−9.7	−11.8
O M2 482	16	−1.3	4.0	0.8	−3.2	−13.0	−1.0	−12.3	−13.3
O M2 484	14	−2.3	2.9	−0.7	−3.6	−11.5	−1.7	−10.9	−12.6
O M3 205	19	0.2	4.0	2.5	−1.6	−11.2	−1.6	−10.3	−12.0
O M3 318	20	−0.6	4.3	1.9	−2.4	−10.8	−1.2	−10.2	−11.4
O M3 478	14	0.0	5.2	2.1	−3.1	−10.6	−1.8	−9.8	−11.6
TR M2 725	18	0.6	2.2	1.9	−0.4	−10.5	−2.8	−8.9	−11.7
TR M2 763	17	0.9	2.6	2.2	−0.4	−11.6	−3.0	−9.7	−12.7
TR M2 831	17	0.9	2.3	2.4	0.1	−11.0	−5.6	−7.6	−13.2
TR M3 725	16	0.8	2.0	1.9	−0.1	−10.5	−4.2	−8.3	−12.5
TR M3 763	15	1.3	2.5	2.6	0.1	−11.7	−3.0	−10.3	−13.2
TR M3 831	13	0.6	2.4	1.4	−1.0	−10.5	−3.5	−9.1	−12.5

in amplitude toward the end of the second molar and a progressive decrease on the third molar. The same individual displays parallel oxygen and carbon isotope sequences in the second molar and an inverse relationship between the two in the third molar. All the other individuals from Baltarga show a parallel relationship between the two isotopic sequences. However, the last part of the crown of the second molar of individual BTB 3271 may suggest the same dynamic as that displayed by individual BTB 3270. Nevertheless, the absence of M_3 values makes it impossible

to verify the presence of the same pattern as in individual BTB 3270.

At Sant Esteve d’Olius, the oxygen sequences show great variation along teeth crowns, following a sinusoidal pattern; the carbon sequences, instead, exhibit a narrower amplitude of variation. All individuals show parallel $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences, with the exception of individual O 205, which displays a parallel sequence along the second molar and an inverse one along the third molar.



The three individuals from Turó de la Rovira show inter-tooth variation in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences. These follow a sinusoidal pattern, with clear maximum and minimum peak events, which are absent in the third molar of individual TR 831 due to the young age and, consequently, the incomplete mineralisation of the crown. The oxygen values of these individuals are the highest among those recorded in all the teeth of the studied sites, as well as those with a lower amplitude (Figure 3). Two individuals, TR 725 and TR 763, show a positive correlation between the oxygen and carbon sequences in both M_2 and M_3 . A different pattern is recorded in the M_2 and M_3 of individual TR 831, which shows an inverse relationship between the two sequences.

3.3. Strontium isotopic ratios

The $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios and Sr concentrations (ppm) from the twelve teeth are shown in Table 3 and Figure 4. Overall, strontium concentrations in sheep tooth enamel ranged between 59 and 365 ppm, with strontium isotope ratios ranging from 0.70914 to 0.71471.

At Mas Castellar de Pontós, the two samples taken from the M_2 of individual 20160 and the sample from the corresponding M_3 have a strontium concentration between 300 and 365 ppm and a narrow $^{87}\text{Sr}/^{86}\text{Sr}$ range (between 0.71447 and 0.71471).

The three samples collected from individual 3270 of Tossal de Baltarga (one sample from the M_2 and two from the M_3) exhibit a strontium concentration between 59 and 116 ppm and a wide variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.70967 and 0.71194.

At Sant Esteve d'Olius, eight samples were taken from three individuals (O 174, O 205, O 484) and their strontium concentration ranged between 161 and 285 ppm. Seven out of the eight samples cluster closely (between 0.70914 and 0.70955). The sample taken from the M_2 of individual O 205 differs, with an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.71019. This indicates a significant variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between M_2 and M_3 of this individual.

The five samples collected from two individuals from Turó de la Rovira (TR 725 and TR 831) exhibit strontium concentration between 107 and 128 ppm, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.70965 to 0.71016. Individual TR 725 displays a very narrow range of values between 0.71008 and 0.71016, whilst individual TR 831 shows variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, ranging from 0.70965 to 0.71016.

TABLE 3 $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and strontium concentration (ppm) from the lower second (M_2) and third (M_3) archaeological sheep molars; the surface and lobe of the tooth where the sampling was carried out are indicated.

Sample ID	Tooth surface	Tooth lobe	$^{87}\text{Sr}/^{86}\text{Sr}$	ppm
MC M2 20160.1	Buccal	Anterior	0.71454	365
MC M2 20160.2	Buccal	Anterior	0.71471	329
MC M3 20160	Buccal	Anterior	0.71447	300
BTB M2 3270.1	Buccal	Anterior	0.70967	116
BTB M3 3270.1	Buccal	Anterior	0.71026	103
BTB M3 3270.2	Buccal	Anterior	0.71194	59
O M2 174.1	Buccal	Anterior	0.70947	285
O M2 174.2	Buccal	Anterior	0.70928	269
O M2 205	Buccal	Anterior	0.71019	161
O M3 205.1	Buccal	Anterior	0.70914	276
O M3 205.2	Buccal	Anterior	0.70914	199
O M2 484.1	Buccal	Anterior	0.70955	279
O M2 484.2	Buccal	Anterior	0.70947	240
O M2 484.3	Buccal	Anterior	0.70937	240
TR M2 725	Lingual	Distal	0.71008	128
TR M3 725	Lingual	Middle	0.71016	107
TR M2 831	Lingual	Distal	0.70967	115
TR M3 831.1	Buccal	Anterior	0.70965	124
TR M3 831.2	Buccal	Anterior	0.71016	123

4. Discussion

4.1. Altitudinal mobility during the 3rd c. BC in the north-eastern Iberian Peninsula

Mas Castellar de Pontós is the only one of the four sites analyzed that does not feature individuals practising altitudinal mobility. Previous studies have provided a picture of a complex herding system within the rural establishment. A bi-modulated reproduction pattern, with births occurring from late winter to late spring and in autumn (Messana et al., 2023), as well as a prevalence of adult and old individuals (Colominas, 2008, 2013), suggest intensive exploitation of secondary products (i.e., milk and wool) throughout the year. The mild and humid climate (Pons et al., 2010; González-Sampériz et al., 2017) and the availability of crop residues resulting from the presence of both winter and spring cultivations provided the inhabitants of Mas Castellar de Pontós with all the conditions necessary to breed and sustain the flocks all year round. Indeed, the $\delta^{13}\text{C}$ values of the individuals from the rural settlement are the highest among all the samples analyzed in this study. This suggests the consumption of C_3 plants supplemented with C_4 plants, likely the spring cereals cultivated in the settlement. However, further investigations are required to thoroughly explore this possibility. Ongoing isotopic analysis, including not only faunal remains but also plants, human remains, and soils from the site, will provide a more comprehensive picture

of the dietary practices within the settlement. At Mas Castellar de Pontós, therefore, there was no environmental or economic necessity for seasonal altitudinal mobility, as the management and exploitation of the herd were suited to a sedentary herding system. The three $^{87}\text{Sr}/^{86}\text{Sr}$ values displayed by individual 20160 (0.71447, 0.71454, 0.71471) are not significantly different from one another, consistent with the individual remaining in the same area throughout its tooth-crown formation (Figure 5). Therefore, both isotopic proxies indicate a sedentary mobility pattern. On the other hand, the high strontium values observed are not consistent with the local geology based on the information derived from the geological map of the Alt Empordà. However, it must be kept in mind that the absence of a bioavailable strontium baseline for this area limits the interpretation of these data. In the same way, this limitation also affects any prediction about the biosphere strontium signal around the settlement. Future studies focused on providing a first baseline of bioavailable strontium in the area are therefore necessary in order to continue and deepen the interpretation of the data.

At Tossal de Baltarga, individuals BTB 3249 and BTB 3271 show a very narrow amplitude during all the carbon sequences, suggesting limited to no changes in consumed plant resources during their first year of life. The same dynamic is recorded in individual BTB 3031 during its second year of life. Therefore, it is likely that these individuals fed in the same place, the Cerdanya mountain valley, exploiting local resources. The positive correlation of their $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences confirms the sedentary pattern. Individual BTB 3270 displays, however, a different scenario. In fact, in its second year of life, there is a simultaneous increase in carbon isotope values and a decrease in oxygen isotope values, resulting in an inverse relationship between the two sequences. The increase in carbon isotope values reflects the consumption of carbon-enriched plants in a drier environment, suggesting a change in diet due to altitudinal mobility. The data indicate that individual BTB 3270, during its second year of life, joined the practice of vertical mobility after summer by descending to lowland locations. After its second winter, there is a new change of altitude and a return to the original location, within an annual vertical movement. The low oxygen isotope values observed in sheep specimens from Tossal de Baltarga, located on the western Spanish Pyrenees, are consistent with a high-altitude environment, as reported by Knockaert et al. (2018) for the Western French Pyrenees. The wear stage of individual BTB 3270's M_2 does not allow for the visualization of its first summer oxygen values, and the young ages of individuals BTB 3249 and BTB 3271 (21–24 months and 2–3 years, respectively) precludes reconstructing their second summer. Nevertheless, it cannot be excluded that individuals BTB 3249 and BTB 3271 followed a similar mobility pattern as individual BTB 3270, as suggested by the similarity of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences of their second molars. The limited time frame of births at the site, from late winter to mid-spring (Messana et al., 2023), supports the idea that the three individuals may have experienced similar environmental conditions and mobility patterns. However, the absence of the respective third molars and the incomplete mineralisation of the final part of the crowns limit the confidence of this hypothesis. The M_3 of the individual BTB 3031 shows higher oxygen and lower carbon isotope values compared to the

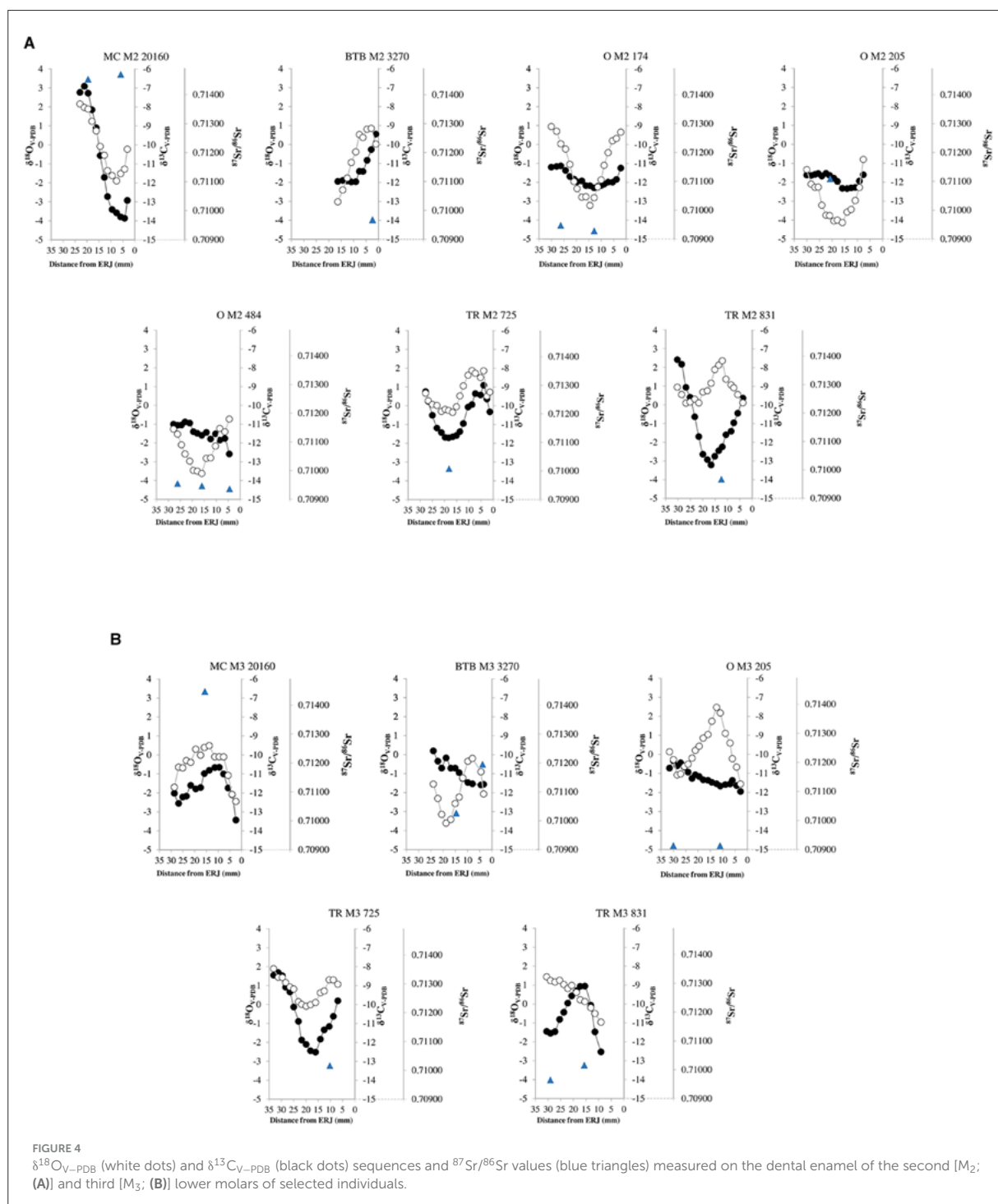
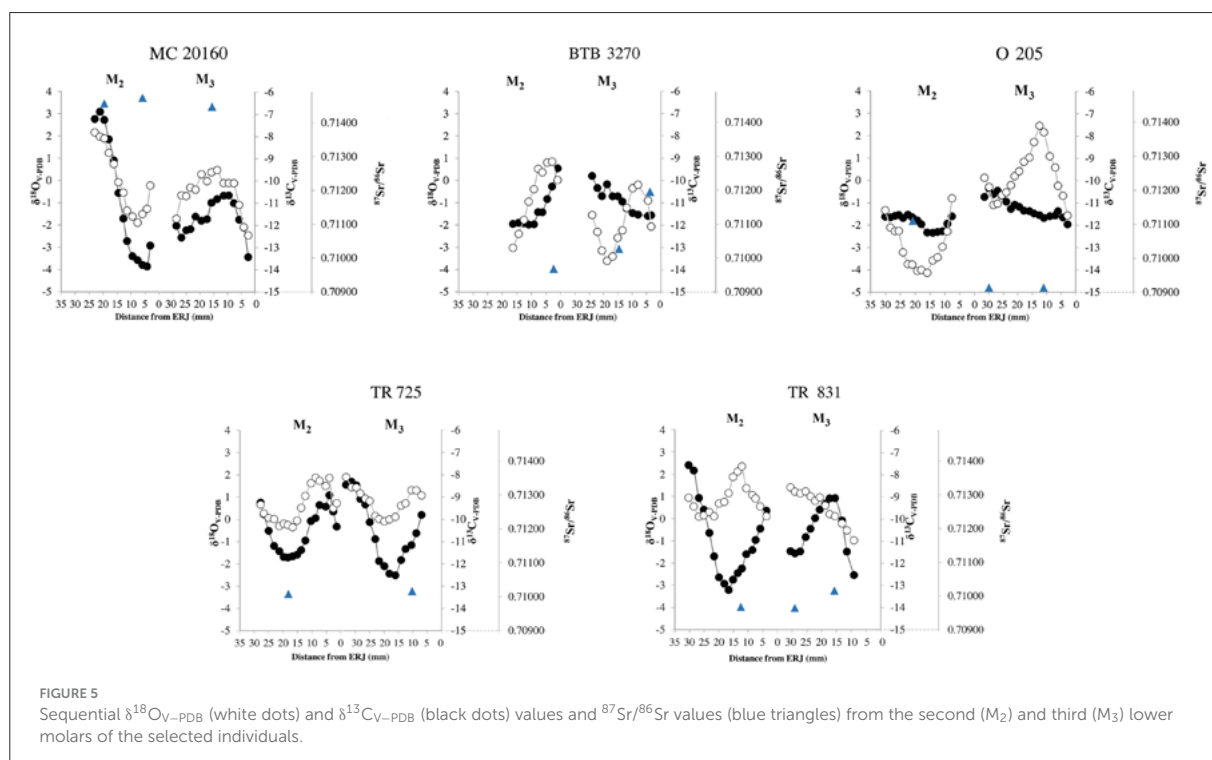


FIGURE 4

$\delta^{18}\text{O}_{\text{V-PDB}}$ (white dots) and $\delta^{13}\text{C}_{\text{V-PDB}}$ (black dots) sequences and $^{87}\text{Sr}/^{86}\text{Sr}$ values (blue triangles) measured on the dental enamel of the second [M_2 ; (A)] and third [M_3 ; (B)] lower molars of selected individuals.

M_3 of the individual BTB 3270. Moreover, the two sequences are parallel and therefore do not show signs of altitude mobility. Three samples were collected from the individual BTB 3270 for strontium isotope analysis (one from the M_2 and two from the M_3). The three $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.70967, 0.71026, 0.71194) vary substantially from each other, indicating a probable change of pasture during the first

2 years of life (Figure 5). Once again, the strontium isotope analysis results support what was inferred from the relationship between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences, in this case an inverse one. The predicted $^{87}\text{Sr}/^{86}\text{Sr}$ values for the surrounding area of Tossal de Baltarga range between 0.708 and 0.709, in line with the value recorded by individual BTB 3270 during its first summer spent in the settlement



area. The other two values diverge from the expected local range. The second value shows the isotopic signal recorded during the individual's second winter spent in the lowlands. Whereas the third value, covering the third summer, probably reflects the signal recorded during the return journey to Cerdanya.

Almost all the individuals from Sant Esteve d'Olius exhibit a sedentary behaviour. Individual O 205 is the only exception, since it moved from a different location to Olius during its third winter. The $\delta^{18}\text{O}$ values observed in the M_2 during the second winter are significantly lower than those recorded in the M_3 over the following two winters. Furthermore, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences switch from being parallel in the M_2 to being inverse in the M_3 . Therefore, Individual O 205 made a unidirectional movement toward Olius, where it remained for the rest of its life, and not a seasonal one. Moreover, the low $\delta^{18}\text{O}$ values suggest that the individual came from higher altitudes. Supporting this hypothesis, such low oxygen isotope values are not reported among the other individuals from the site. Individual O 348 may follow the same pattern as individual O 205, as evidenced by the fact that the M_2 exhibits lower $\delta^{18}\text{O}$ values than the other individuals. However, the absence of the M_3 makes it impossible to track the eventual change in altitude. Three individuals were sampled for strontium analyses: O 174, O 205, and O 484. The $^{87}\text{Sr}/^{86}\text{Sr}$ values from the M_2 s of individuals O 174 (0.70947, 0.70928) and O 484 (0.70955, 0.70947, 0.70937), and those from the M_3 of individual O 205 (0.70914, 0.70914) are very similar to each other and consistent with those expected for this area, supporting their sedentary behaviour. In contrast, the $^{87}\text{Sr}/^{86}\text{Sr}$ value from the M_2 of individual O 205 is significantly different (0.71019; Figure 5). This variation would confirm the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ results and thus indicate a unidirectional movement of

individual O 205 toward Olius in its third year of age. Further confirmation is provided by the highly homogeneous lithology of the Solsonès region, as reflected by the extremely similar strontium isotope values observed in the analyzed individuals. The only value that diverges is precisely the one recorded in the M_2 of individual O 205, indicating its exogenous origin.

Out of the three individuals from Turó de la Rovira, only one, TR 831, shows a mobility pattern. After its first winter, an increase in oxygen values coincides with a decrease in carbon isotope values, indicating a movement toward a wetter environment and resulting in a change in diet. After the second summer, a new change in pasture occurs, reflected by a decrease in oxygen isotope values and a simultaneous increase in carbon isotope values. Individual TR 831, therefore, spent its second summer in a wetter area, before returning to Turó de la Rovira and staying there during its second winter. However, the recorded oxygen values are not compatible with high-altitude environments (Knockaert et al., 2018). It is therefore likely that the one practised at Turó de la Rovira was a type of short-range seasonal mobility, with a not very high altitudinal gradient. Individuals TR 725 and TR 831 were sampled for strontium analyses. The $^{87}\text{Sr}/^{86}\text{Sr}$ value from the M_2 and the M_3 of individual TR 725 (0.71008 and 0.71016), sampling at the oxygen winter and summer peaks respectively, are extremely similar to each other and consistent with the expected values surrounding the settlement, supporting the sedentary behavior of the individual (Figure 5). The $^{87}\text{Sr}/^{86}\text{Sr}$ value from the M_3 of individual TR 831 (0.71016), sampling at the oxygen peak of the second winter, is in line with the values of the previous individual, providing further evidence for a return to Turó de la Rovira during the second winter. In contrast, the two $^{87}\text{Sr}/^{86}\text{Sr}$

values obtained from the samples taken at the oxygen peak of the second summer in M₂ and M₃ show different results compared to the previous values (0.70967, 0.70965; Figure 5), and lower than the expected range. Therefore, strontium isotope analysis results support the seasonal vertical mobility performed by individual TR 831.

4.2. Iberian livestock mobility strategies

The data evidence the use of different livestock mobility strategies by Iberian communities: seasonal altitudinal mobility between two different ecosystems, unidirectional mobility, and short-range seasonal mobility along a low altitudinal gradient. Adopting a model of seasonal altitudinal mobility of herds must be sustainable and motivated by specific environmental and/or economic reasons. Indeed, this type of pastoralism implies a specialization of livestock breeding and comprehensive knowledge of both the surrounding environment and the availability of natural resources. It also required the free movement of flocks ensured by prior communication with the relevant populations, the ability to manage any disruptions that may occur during flock displacements, such as diseases and injuries, and the possibility of commercial opportunities (Brun, 1996; Euba, 2008; Oteros-Rozas et al., 2012). In settlements such as Mas Castellar de Pontós, where the herding system shows complex organization, the availability of fodder could be ensured throughout the year, and neither the environment nor commercial and exchange interests may induce mobility, sheep husbandry remains sedentary.

The shepherders of Tossal de Baltarga were faced with different necessities and had to devise more ingenious responses. Their livestock strategies had to adapt to the harsh Pyrenean winter, with reduced vegetation covered by snow during cold season of the year. A first response to the environmental restrictions was the anthropogenic manipulation of the lambing period, with a reduced duration (2.5 months) and natural births in late winter/mid-spring (Messana et al., 2023). In this way, the care labor for pregnant ewes and newborns was minimized, and the latter did not have to face the classic cold winter temperatures in high mountain locations. An additional strategy adopted by shepherds was to integrate part of the herd in the practice of seasonal vertical mobility to lowland pastures, where they would spend overwinter. Between the end of the Bronze Age and the Early Iron Age, there was a decrease in vegetation cover in the high mountain areas of the Pyrenees. This seems to be linked to an increase in husbandry and agriculture in these areas (Euba, 2008; Morera, 2017; Olesti and Mercadal, 2017). It was suggested that the vertical seasonal movements undertaken by flocks took place between the Cerdanya plain, frequented during winter, and the high mountain areas, exploited in the summer (Euba, 2008; Knockaert, 2017; Morera, 2017; Olesti and Mercadal, 2017). In the study carried out by Knockaert et al. (2018), $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences from two Middle and Late Bronze Age sites were analyzed: Llo, located in the Cerdanya high mountain area (1630 m a.s.l.), and Portal-Vielh, situated on the eastern coast of present-day France (0 m a.s.l.). The data obtained from the isotope analyses revealed a sedentary pattern for the coastal herd and a variety of patterns in the sequences of

the high-mountain individuals, including two sequences with an inverse relationship. This great diversity of profiles is interpreted by the authors as the adoption of different husbandry strategies to cope with a mountainous environment characterized by significant inter-annual climatic variations. Seasonal altitudinal mobility could be one of these strategies, although none of the individuals analyzed in the study exhibit profiles similar to those measured in modern references from lowlands areas, which were used by the authors as baselines. Seasonal movements of the herd toward lower altitudes would, therefore, be excluded, suggesting the exploitation of medium and high mountain areas and a full adaptation to the mountain environment during this period. From the 5th century BC, the Ceretans centralized their settlements in the middle and lower Cerdanya and focused on agricultural production (Olesti and Mercadal, 2017). Furthermore, a new territorial pattern is witnessed in Cerdanya, with *oppidum*-type settlements (Morera, 2017; Olesti and Mercadal, 2017). In this context, the one reported at Tossal de Baltarga is the first evidence of vertical descendant mobility from the Ceretan region to the lowlands. As previously reported, individual BTB 3270 displays clear signs of mobility, and individuals BTB 3249 and BTB 3271 seem to follow the same pattern. All three individuals came from the same building (G). On the other hand, individual BTB 3031, coming from a different building, shows sedentary behaviour. Bearing in mind the small number of individuals recovered from the Iberian phase of the settlement, the available data suggest great flexibility in husbandry practices at Tossal de Baltarga, where only part of the flock spends the summer at lower altitudes. Is this selective mobility the result of the independent movement of individual family groups to the lowlands, or is it a planned strategy by the entire Tossal de Baltarga community? The presence of several buildings with specialized production areas in the settlement, along with the discovery of luxury objects and a horse, suggest the existence of an elite class (Morera, 2017; Olesti et al., 2018; Tàrraga, 2020), that could be the responsible for the herd. The seasonal altitudinal movement carried out by individuals from building G could be part of a complementary, diversified strategy, in which part of the flock remained in the Ceretan territory while part moved to the valley. The displacement of just a part of the flock could have resulted from a reduction in pasture availability during the winter, or from the decision to maintain part of the flock at Tossal de Baltarga for domestic consumption. Furthermore, it cannot be ruled out that this altitudinal movement was not exclusively related to a seasonal complementarity between pastures, but could also have been part of a commercial exchange relationship with lowland populations. Finally, it cannot be excluded that multiple small flocks from different settlements in the Ceretan area were combined into a single large flock that moved toward the lowlands. This scenario would suggest a collaborative approach among the Ceretan communities, where they coordinated their herding activities to optimize resources and maximize efficiency.

The presence of one individual at Sant Esteve d'Olius with external provenance to Solsonès, along with the potential occurrence of a second one, points to unidirectional type of mobility, distinct from the seasonal pattern observed in the previous case. Sheep from high-altitude areas, most likely the Pyrenees, might have arrived at the site for commercial purposes involving product exchange. This could have allowed Lacetan

shepherds to diversify and/or renew their livestock by engaging in exchanges with populations from higher mountain regions. Solsonès is renowned for its production and trade of rock salt, which is necessary not only for preserving meat or cheese production but also for feeding livestock (Olesti and Mercadal, 2017). Sheep, in fact, need salt as an essential nutrient, and rock salt, with its higher sodium chloride content and purity compared to sea salt, is often preferred (Titler and Curry, 2011; Luna Loayza, 2013; Manrique, 2017; Marcos Pinto, 2019). Furthermore, it is also easily transported as blocks (Weller, 2004; Olesti and Mercadal, 2017). The earliest evidence of rock salt exploitation in the *Muntanya de Sal* of Cardona, just over 20 km from Sant Esteve d'Olius, dates back to the Middle Neolithic (Weller, 2002; Weller and Figuls, 2007; Figuls et al., 2013). During Roman times, salt was established as a state monopoly and subjected to specific taxation (Olesti and Mercadal, 2017; Olesti, 2022). Furthermore, the existence of a control point in the Cardona production area dating back to the 2nd–1st centuries BC is known (Olesti and Mercadal, 2017). The rock salt extracted from Cardona was transported to Gaul and Italy via a route that traversed Solsonès, Alt Urgell, and Cerdanya before reaching the present-day French territory (Obiols et al., 2009). Livestock directed toward the summer pastures of the Pyrenees would have followed the same path (Obiols et al., 2009; Olesti, 2022). During medieval times, it was the so-called *strata Kardonensis*, a key route for the supply of rock salt, that connected Solsonès to the Eastern Pyrenees (Olesti and Mercadal, 2017; Olesti, 2020). In modern documents, this route appears under the name *camí Cardoner* or *camí saliner de Cardona* and was used until the first half of the 20th century (Obiols et al., 2009; Guardia and Obiols, 2014). Therefore, the Solsonès-Cerdanya axis is well-documented over the centuries. At Sant Esteve d'Olius, the presence of at least two individuals from high-altitude areas is attested, while at Tossal de Baltarga at least one individual moves seasonally toward the lowlands. In these cases, the exact location of the origin or destination cannot be determined. Nevertheless, the hypothesis that the movements recorded in the two settlements through this study are interconnected as part of a commercial relationship between the mountainous Ceretan region and the rich pre-Pyrenean Iberian zone should not be dismissed. The high-mountain resources (wood, summer pastures, livestock) were likely of interest to the pre-Pyrenean centers, just as those of the Solsonès (salt, pastures for wintering, Mediterranean imports) would have been appealing to the Ceretans (Olesti and Mercadal, 2017).

At Turó de la Rovira, a few kilometers from the Mediterranean coast, seasonal mobility occurs along a low altitudinal gradient. The Mediterranean basin is characterized by a tendency to dryness during summer, resulting in limited fodder resources (Jalut et al., 2009; Reiser and Kutiel, 2010; Turco et al., 2017). The evidence for seasonal vertical mobility at Turó de la Rovira is therefore not surprising. However, only one of the three individuals analyzed moves and spends its second summer in wetter pastures. This individual is also the only one to be born in summer, unlike the other two individuals who were born in spring (Messana et al., 2023). This suggests that despite the potential challenges of limited water and food resources during the summer, the sedentary portion of the herd was able to survive in the settlement. A previous study on the reproductive strategies adopted at Turó de la Rovira showed the presence of a single group of births, but with a

longer lambing period than the natural one and the product of anthropogenic scheduling (Messana et al., 2023). In fact, births occur throughout a period of 3.5 months, from winter to early summer. Various hypotheses have been suggested to interpret this birth management. It could be the result of planning within the agro-pastoral calendar or a process of arranging for a 'de-seasoning' of the herd in the autumn or the result of a 'catch-up mating' set up to compensate for the low spring fertility. Therefore, the data on livestock mobility strategies presented in this study reinforce the idea of a differentiated flock management strategy, while pointing toward a division of the herd into two distinct groups. Thus, part of the flock remained in Turó de la Rovira, while other individuals, starting from the second year of life, joined the practice of seasonal altitudinal mobility. The decision not to move the entire herd may have been aimed at reducing the farmers' workload during the intense summer months of agricultural activity (Cleary, 1986). Supporting this hypothesis, carpological data reveals a predominant cultivation of wheat and barley, along with the presence of millet and, in minor quantities, legumes, grapes, and figs (Riera et al., 2020). Furthermore, the migration of only a portion of the flock could depend on the limited availability of pasture during the dry summer season or, as suggested in the case of Tossal de Baltarga, on the intention of maintaining part of the herd in the settlement for domestic consumption. Finally, short-range livestock mobility generally involves small flocks (Brun, 1996). The nearby coastal massif of the Garraf (Baix Llobregat, Barcelona) can be hypothesized as the destination for the seasonal movements from Turó de la Rovira. The presence of several pastoral enclosures dated to the Iberian period (6th–1st century BC) provides evidence of the passage and housing of livestock in this area (Cebrià et al., 2003; Ejarque and Orengo, 2009). Moreover, anthropological data from the Late Bronze to Early Iron Age indicate a reduction of the vegetation on the massif as a result of anthropogenic pressure (Ros Mora, 1992; Riera et al., 2007). The already mentioned study by Valenzuela-Lamas et al. (2018) provides a first baseline of bioavailable strontium for the area around the Iberian site of Turó de la Font de la Canya (Avinyonet del Penedès, Barcelona), located on a small coastal promontory between the Penedès plain and the Garraf Massif. The ⁸⁷Sr/⁸⁶Sr values recorded by individual TR 831 during the second summer spent away from Turó de la Rovira are lower than the expected local ones and could be compatible with a movement toward the Vallès-Penedès depression and the Garraf massif.

5. Conclusion

Based on the results of this study, new insights into the mobile herding systems adopted by Middle/Late Iron Age communities in the north-eastern Iberian Peninsula are proposed. The integration of strontium, carbon, and oxygen isotope analyses on sheep from four distinct sites has demonstrated the complexity of animal husbandry practices and the adaptability in mobile livestock strategies employed by Iberian populations. During the Iron Age, Iberian herders possessed extensive knowledge and expertise in sheep breeding, management, and exploitation and could overcome challenges posed by harsh mountain winters and arid lowland summers. The adoption or not of a mobile strategy was therefore

strictly linked to the specific necessities of each settlement, and probably dictated by herd management and economic reasons. As a result, the four sites examined in this study provided four different husbandry models: Mas Castellar de Pontós displays a sedentary herding system; at Tossal de Baltarga, the only high-altitude settlement, part of the herd practised seasonal altitudinal mobility between two complementary ecosystems; a unidirectional type of mobility is detected at Sant Esteve d'Olius, with the aggregation of sheep with external provenance into the flock; lastly, at Turó de la Rovira, a portion of the herd practised seasonal mobility along a low altitudinal gradient.

Tossal de Baltarga presents the first evidence of seasonal altitudinal movements between the lowlands and the Pyrenees, prior to the Roman conquest. Moreover, the presence of at least one individual from high altitude areas, most likely the Pyrenees, at Sant Esteve d'Olius, suggests similar behaviour. These data, therefore, pave the way for the image of a more integrated and connected Ibero-Pyrenean world with its contemporary lowland (and highland) communities. Furthermore, mobile pastoralism not only requires but also creates social interactions and connections between various regions and communities. The Iberian societies of the 3rd c. BC must therefore have established a robust network of social and economic relations on which a mobile farming system relied. The latter could count on the state entities that emerged and consolidated during the Iron Age, which provide the necessary economic and socio-political framework. What is clear, however, is that this animal mobility was not general and that was likely practised only when necessary and/or economically profitable. In this regard, we want to highlight the results obtained in [Messana et al. \(2023\)](#), which also show diversified sheep reproductive patterns and distinct demographic management in the four settlements under study here. Although a major number of sites are required for analysis in the following studies, our data suggest that livestock mobility strategies in each settlement were determined by their own environmental conditions, economic needs, and political decisions. Extending the research to the Roman period is required in order to properly investigate if animal mobility patterns increase during this period as other archaeological evidences seem to show. Additionally, we consider it imperative to enlarge the investigation to other Iron Age Catalan settlements. This broader approach would allow for a multi-site analysis and verify the potential to formulate a more complete model of livestock strategies.

In addition to providing a more comprehensive understanding of livestock management by north-eastern Iberian communities, this study provides significant methodological insights. Indeed, it proves the effectiveness of integrating data obtained from sequential analysis of carbon and oxygen values with strontium isotope ratios. In fact, a correspondence and complementarity exist between the results obtained through the inverse relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ and those derived from $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Thus in individuals in which the parallel sequences of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ indicate a sedentary behaviour, the values of $^{87}\text{Sr}/^{86}\text{Sr}$ exhibit no significant differences. On the other hand, in individuals displaying an inverse relationship between the two sequences, the $^{87}\text{Sr}/^{86}\text{Sr}$ values vary significantly between them, confirming a movement between different geological areas. Nevertheless, it must be kept in mind that if altitudinal movement occurs between areas with the same lithological composition, it will not be

detected by strontium analysis alone. To effectively trace movement along different altitudinal and geological zones and explore the locations of origin and destination in deeper detail, a multi-isotope analysis approach is essential. In conclusion, the results presented in this article add new and fundamental information on livestock management and, in particular, mobile herding strategies adopted by Iberian communities during the Middle/Late Iron Age. Furthermore, they highlight the huge potential provided by multi-isotope analyses when it comes to trace evidence of livestock movements along different altitudinal and geological areas.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements because the manuscript contains studies of archaeological faunal remains. In the Acknowledgments, it is stated that the directors of the four sites granted permission for the analysis and study of the materials. In Material and methods there is a clear description of the sampling procedures carried out on the remains.

Author contributions

CM wrote the main manuscript, prepared figures, processed the data, and selected and prepared the samples for oxygen and carbon isotope analysis and prepared the samples for strontium isotope analysis. CT, RM, AL, JE, and LC reviewed the manuscript. CM, CT, LC, and RM have acquired the funding. CM and CT selected the samples for strontium isotope analysis. RM supported the samples preparation for strontium isotope analysis. JE undertook all $^{87}\text{Sr}/^{86}\text{Sr}$ isotope mass spectrometry. All authors contributed to the article and approved the submitted version.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fearc.2023.1245725/full#supplementary-material>

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4.3 Feeding strategies

The third key element of a husbandry system discussed in this thesis is the alimentation of the flock. To obtain information on the feeding habits of sheep, this study combined the sequential analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values performed on dental enamel with the isotopic analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values on bone collagen. In addition to sheep, other domestic and wild species recovered from the four Catalan sites studied were measured to establish the local isotopic baseline of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. The following article, currently under review, and titled “Beyond the herd: investigating livestock feeding strategies in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope analysis”, reveals for the first time the livestock feeding strategies adopted during the Middle/Late Iron Age in the north-eastern Iberian Peninsula.

4.3.1 Paper 3. Beyond the herd: investigating livestock feeding strategies in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope analysis

This manuscript, the final one of this PhD thesis, reveals the complex and adaptive nature of the livestock feeding strategies adopted by Iron Age Iberian communities. Sheep, the predominant species during this period, generally display minimal variation in their diet across all four sites. Nevertheless, their feeding habits exhibit seasonal variations depending on the requirements of each settlement and the availability of pastures. Indeed, different patterns of sheep diet management are observed at the four sites studied on a seasonal level. Individualised feeding strategies were adopted for the other main domestic species, featuring complex

and diverse management practices in each settlement. This species-specific focus on diet required advanced husbandry knowledge, environmental adaptability, and a significant labour force. This study proves that livestock husbandry played a more significant role in the economy of Iron Age Iberian communities than previously acknowledged.

The results of this study demonstrate the complementarity of the isotopic analyses on the organic fraction of bone remains and the mineral fraction of dental remains. The combination of the two proxies provides a comprehensive understanding of the feeding strategies adopted by Iron Age Iberian herders. Finally, the extensive number of remains and the diverse array of species analysed offer the first baseline for the interpretation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results for this chronology and geographical area.

Beyond the herd: investigating livestock feeding strategies in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope analysis

MESSANA Chiara^{1&2*}; TORNERO Carlos^{3&1*}; COLOMINAS Lúdia ⁴

¹ *Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Tarragona, Spain (ES)*

² *Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, 43002 Tarragona, Spain (ES)*

³ *Department of Prehistory, Autonomous University of Barcelona (UAB), Bellaterra, Spain (ES)*

⁴ *Institut Català d'Arqueologia Clàssica (ICAC-CERCA), Tarragona, Spain (ES)*

Abstract

During the Iron Age, north-eastern Iberian communities relied on crop cultivation and animal husbandry for their subsistence. The latter was mainly focused on caprine, with sheep being prominent due to their suitability to the Mediterranean climate, orography, and environment. Despite the pivotal role of sheep in livestock husbandry, information on Iberian communities' feeding strategies for this species is limited. To address this lacuna, this study investigates the livestock feeding habits at four Catalan sites dating back to the 3rd century BC: Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira. Bulk carbon and nitrogen isotope analyses ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of bone collagen and sequential carbon and oxygen analyses ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of dental enamel were performed on 74 remains (43 bones, 31 teeth) from 51 sheep. Additionally, 153 bone remains from other domestic and wild species from the four sites were analysed.

Our results revealed the complex and adaptive livestock feeding strategies of Iron Age Iberian populations. Sheep exhibited minimal diet variations, mainly consuming C_3 plants across the four sites. Nevertheless, their feeding habits changed seasonally depending on pasture availability and settlement requirements. The other main domestic species were subject to individualised and variable feeding strategies within the same settlement. This diversified feeding management suggests a crucial role for animal husbandry in the economy of Iron Age Iberian communities. Finally, the massive number of remains analysed provides the first data on livestock feeding strategies for the Middle/Late Iron Age in the north-eastern Iberian Peninsula.

Keywords: animal diet · stable isotopes · $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ tooth bioapatite · bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values · Iron Age communities · NE Iberian Peninsula

* Corresponding authors:

Chiara Messana, email address: cmessana@iphes.cat

Carlos Tornero, email address: Carlos.Tornero@uab.cat

ORCID number:

MESSANA, C. ORCID ID: 0000-0002-6188-9603

TORNERO, C. ORCID ID: 0000-0002-2870-8989

COLOMINAS, L. ORCID ID: 0000-0001-6838-5814

1. Introduction

1.1 *Setting the Stage: Historical context and aim of the research*

The Iron Age Iberian communities in the north-eastern Peninsula were organised into hierarchical proto-state structures (Gracia 2005; Almagro-Gorbea 2014; Sanmartí 2014, 2021). The settlement pattern was organised through a network of interconnected open-air centres, developed around central nuclei, the so-called first-order cities. These settlements included fortified centres, rural establishments, small villages, and silo fields, each with specific functions (Gracia 2005; Sanmartí 2014, 2021). The subsistence strategies of these communities were based on peasant economies. Cereal agriculture was the main source of subsistence. In the north-eastern Iberian Peninsula, crop cultivations were dominated by wheat (*Triticum aestivum/durum*) and barley (*Hordeum vulgare*), supplemented by millet (*Panicum miliaceum*) and leguminous plants (*Lens culinaris*, *Pisum sativum*, *Vicia faba*) as secondary crops (Alonso 2000; Riera *et al.* 2020). A high level of complexity in crop management has been attested, including potentially the use of rotation cycles in cultivation practices (Alonso 2000; Riera *et al.* 2020). In addition to crop cultivation, herding practices were also a fundamental activity to ensure both the growth and sustainability of these Iron Age communities.

Over two decades of zooarchaeological research have allowed the characterisation of livestock husbandry during that time and in that region. Livestock management included diversification in the exploitation of different domestic species (sheep, goats, cattle, pigs, dogs, horses, rabbits, and chicken), allowing the reduction of dependence on a single species and the obtaining of diversified animal resources (Franquesa *et al.* 2000; Colominas 2006). In this scenario of self-dependence, sheep was the most important species for the economies of the time, as a result of its adaptation to the Mediterranean climate and environment (Miró & Molist 1982a, b; Barbera *et al.* 1986; Casellas 1993; Albizuri and Nadal 1999; Franquesa *et al.* 2000; Perez *et al.* 2007; Colominas 2008, 2013a). This phenomenon can be traced back to the first introduction of this *taxon* in the Iberian Peninsula during the Early Neolithic, around the VI millennium cal BC, and persisted in subsequent periods before the Iron Age (Saña *et al.* 2020; Nieto *et al.* 2021).

Recently, new biomarker studies have provided information on sheep management during this period that is difficult to obtain through traditional zooarchaeological studies. Isotopic oxygen and carbon analyses on sheep molars have documented the complex and diversified husbandry strategies adopted by the Iron Age communities in the north-eastern Iberian Peninsula. When necessary, shepherds intentionally manipulated sheep births, controlling both the seasonality and the duration of the lambing period (Messana *et al.* 2023a). Further, the use of multiple isotopic markers has allowed the investigation of herd management mobility patterns (Valenzuela *et al.* 2016, 2018;), even revealing the existence of altitudinal movements already during this period

(Messana *et al.* 2023b). In both cases (management of sheep reproduction and mobility), the studies show the dependence on the environmental, climatic, and regional context in which livestock farming was practised, documenting differences in the techniques and strategies developed depending on the location of the settlement analysed.

This paper investigates the management of sheep feeding, an aspect for which there is no previous information and which is essential for the exploitation of domestic animals. Furthermore, the adaptation of feeding habits to the different ecological contexts of the north-eastern peninsula must have been a challenge. To achieve this, a biogeochemical approach (stable isotopes) is applied to investigate the feeding strategies employed by shepherds in the north-eastern Iberian Peninsula. Carbon and nitrogen isotope analysis ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of collagen was performed on the bone remains of the main domestic and wild species recovered from four Middle/Late Iron Age settlements: Mas Castellar de Pontós (MC), Tossal de Baltarga (BTB), Sant Esteve d'Olius (O), and Turó de la Rovira (TR). Our results are compared with existing data from sites located in the study area and dating from previous and posterior periods: Bronze Age (BA), Iron Age (IA) and Roman Period (RP). In addition, a portion of the analysed sheep remains was also sampled for the sequential analysis of carbon and oxygen values ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of dental enamel.

The available data on the dietary signals of livestock during the Protohistoric periods in the Iberian Peninsula are limited. Indeed, this research represents the first massive study of livestock feeding strategies during the Middle/Late Iron Age in the north-eastern Iberian Peninsula.

Furthermore, the significant number of individuals and species here analysed could serve as a reference for future research in the same study area.

1.2 Principles: stable isotopes and herding diet

Stable isotope analysis has proven to be a reliable and valuable tool for reconstructing an individual's diet, by measuring the biochemical composition of preserved body tissues in the archaeological record. Isotopic composition of food and water ingested by an animal is recorded in its bones and teeth. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic values from bone collagen provide a quantitative assessment of the protein components of an individual's diet, corresponding to the average food intake during the last 10-15 years of life. This duration corresponds to the time it takes, approximately, for bone collagen to remodel itself during an individual's lifetime (Ambrose 1986; Tykot 2004; Hedges *et al.* 2007). The isotopic signatures recorded in animal tissue differ from those of the initial source consumed as a result of isotopic fractionation. The carbon isotopic fractionation between dietary intake and the consumer is +5‰, and +1‰ from collagen diet to collagen consumer along the trophic chain (DeNiro and Epstein 1978; Schoeninger & DeNiro 1984; Ambrose and Norr 1993; Bocherens and Drucker 2003). The nitrogen isotopic fractionation, on the other hand, is between 3-5‰ at each trophic step (Minagawa & Wada 1984; O'Connell *et al.* 2012; Matsubayashi and Tayasu 2019). The isotopic carbon value measured in bulk collagen derives from the isotopic composition of the plants consumed by an individual. This varies according to the photosynthetic pathways of the plants, i.e. C_3 e C_4 (Bender 1971; Farquhar *et al.* 1989). The average $\delta^{13}\text{C}$ value expected for C_3 plants is -28.5‰, ranging from

-20‰ to -37‰. On the other hand, the threshold above which $\delta^{13}\text{C}$ values are related to C_4 plants is -23‰, with an average value for C_4 plants of -13‰. Extremely low $\delta^{13}\text{C}$ values indicate exclusive consumption of plants grown in closed-canopy forests, with a cut-off of -31.5‰ (Tieszen and Button 1988; Tieszen 1991; Kohn 2010). These values have been calculated in modern plants, whereas for those from pre-industrial times, a correction of +1.5‰ is required to compensate for the fossil fuel effect (Friedli *et al.* 1986; Marino and McElroy 1991; Feranec and MacFadden 2006). C_3 plants are dominant in the vegetation of Western Europe, whilst wild C_4 plants are inexistent or residual in temperate environments (Mateu 1992; Pyankov *et al.* 2010). Therefore, the presence of C_4 plant intake in the studied chronotopic context suggests that animals consumed cultivated C_4 plants, such as millet and foxtail millet. The carbon isotopic signature in collagen also allows discrimination between a diet primarily comprised of either terrestrial or marine foods. Indeed, marine plants exhibit higher values not only of carbon but also of nitrogen (Richards and Hedges 1999; Tykot 2004; Fisher *et al.* 2007).

The isotopic nitrogen value in terrestrial plants mainly depends on the type of nitrogen obtained and the way it is absorbed from the substrate. This can occur either through fixation mediated by symbiotic microbes or directly from soil nitrates (Katzenberg 2000; Evans 2001; Tykot 2004; Szpak 2014). Furthermore, soil nitrogen enrichment can vary as a result of both natural factors (substrate type, degree of soil development, nutrient availability, mycorrhizal associations, soil associations, climate) and anthropogenic ones (i.e. manuring; Bogaard *et al.* 2007; Szpak 2014; Jordana *et al.* 2019; Makhad *et al.* 2022).

The $\delta^{15}\text{N}$ values measured in collagen are used to ascertain the trophic level of an individual within the food web. Indeed, an isotopic signature enriched in nitrogen corresponds to a higher intake of animal protein. Consequently, the $\delta^{15}\text{N}$ isotope values of predators are higher than those of their prey (DeNiro and Epstein 1978; Schoeninger and DeNiro 1984; Katzenberg 2000). However, when comparing individuals from different ecosystems, it is important to take into account the isotopic composition of the local food web (Katzenberg 2000; O'Connell *et al.* 2012). For this reason, it is essential to create a local baseline that enables a correct interpretation of the nitrogen isotope values of each individual.

Once mineralised, dental enamel does not remodel. As a consequence, the mineral fraction of the enamel (i.e. bioapatite compound) reflects the isotopic signature recorded during its formation. In sheep, the crown formation of the second molar (M_2) begins between the first and second month and is completed at 12 months. On the other hand, the third molar (M_3) starts forming from the tenth month onwards and is completed at around 22 months (Milhaud and Nézit 1991; Hillson 2005; Zazzo *et al.* 2010). Each of the two molars individually allows the reconstruction of one year of an individual's life. The information obtained from the combination of the two molars makes it possible to trace back the first two years of a sheep's life. Therefore, the sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis of dental enamel provides a snapshot of an individual's diet and pasture environment during the period of tooth formation. The $\delta^{13}\text{C}$ values measured in dental bioapatite are related to the carbon isotopic composition of the plants ingested by an individual (Lee-Thorp

and Van de Merwe 1987). Large ruminant mammals exhibit an isotope enrichment (ϵ^*) of $14.1 \pm 0.5\%$ between diet and enamel bioapatite (Cerling and Harris 1999). The oxygen isotope values recorded in bioapatite are mainly derived from ingested water and consumed plants (Longinelli 1984; Luz *et al.* 1984). These isotopic signatures are related to meteoric water and temperature, which vary seasonally at temperate latitudes. As a result, at medium and high altitudes, higher $\delta^{18}\text{O}$ values reflect the warm season, whilst lower $\delta^{18}\text{O}$ values are recorded during the cold season (Gat 1980). It is, therefore, possible to detect changes in an individual's diet during the first years of life with a seasonal resolution by combining the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sequences along the tooth crown.

2. Material and Methods

2.1 The sites

The faunal remains selected for this study derive from four settlements with contemporary and well-dated occupations during the 3rd century BC. These sites are located in distinct ecological and cultural areas in the north-east of the Iberian Peninsula (Figure 4.6). Mas Castellar de Pontós is situated on a fertile plain within the northern pre-coastal Catalan region, falling under the territory of *Indigeti*. Ascending to higher altitudes is the *Ceretan* settlement of Tossal de Baltarga, located on the Cerdanya plain, in the Pyrenees. Further inland, the Pre-Pyrenees area hosts the settlement of Sant Esteve d'Olius, settled on the fertile *Lacetan* agricultural plain. Lastly, near the central Mediterranean coast, the *Laietan* site of Turó de la Rovira extends over the Barcelona plain. Agriculture, and specifically crop cereal production, has traditionally been considered the main economic activity in all four

settlements. Indeed, the management, production, storage, and distribution of agricultural surpluses have been documented (Pons *et al.* 2010; Morera 2017; Asensio *et al.* 2008). Three of the sites, excluding Tossal de Baltarga, have revealed archaeological evidence of silo fields. However, the *Ceretan* settlement has preserved, in one of its buildings, large ceramic containers and concentrations of wheat grain, suggesting a probable storage function (Olesti *et al.* 2018). Animal husbandry, mostly focused on caprines, constituted another key activity within the subsistence economy of the four settlements. Indeed, sheep are the most represented species in all the studied sites, followed by goats, cattle, and pigs (Colominas 2013a; Colominas 2013b; Colominas 2019; Colominas *et al.* 2023). The presence of wild *taxa*, either hunted and consumed or present as commensal species, is minor.

Mas Castellar de Pontós is located in the Empordà region (Girona), near the Mediterranean coast, at 154 m a.s.l. The site is situated approximately 17 km equidistant from the Greek colonies of *Rhode* and *Emporion*, on a promontory between two watercourses. Its favourable geographical position made it a strategic communication hub between the coast and the inland regions, as well as between the two Greek colonies and the indigenous inhabitants (Pons *et al.* 2010). Human occupation of the settlement covers a wide chronological frame, spanning from the late 7th century B.C. to the early 2nd century B.C. (Adroher and Pons 2002; Pons *et al.* 2010). The phase here investigated extends between 250 BC and 180 BC, when the site hosted a specialised agricultural settlement associated with an extensive silo field (Pons *et al.* 2010). This rural settlement was under the governance of a rural aristocracy and played a crucial role

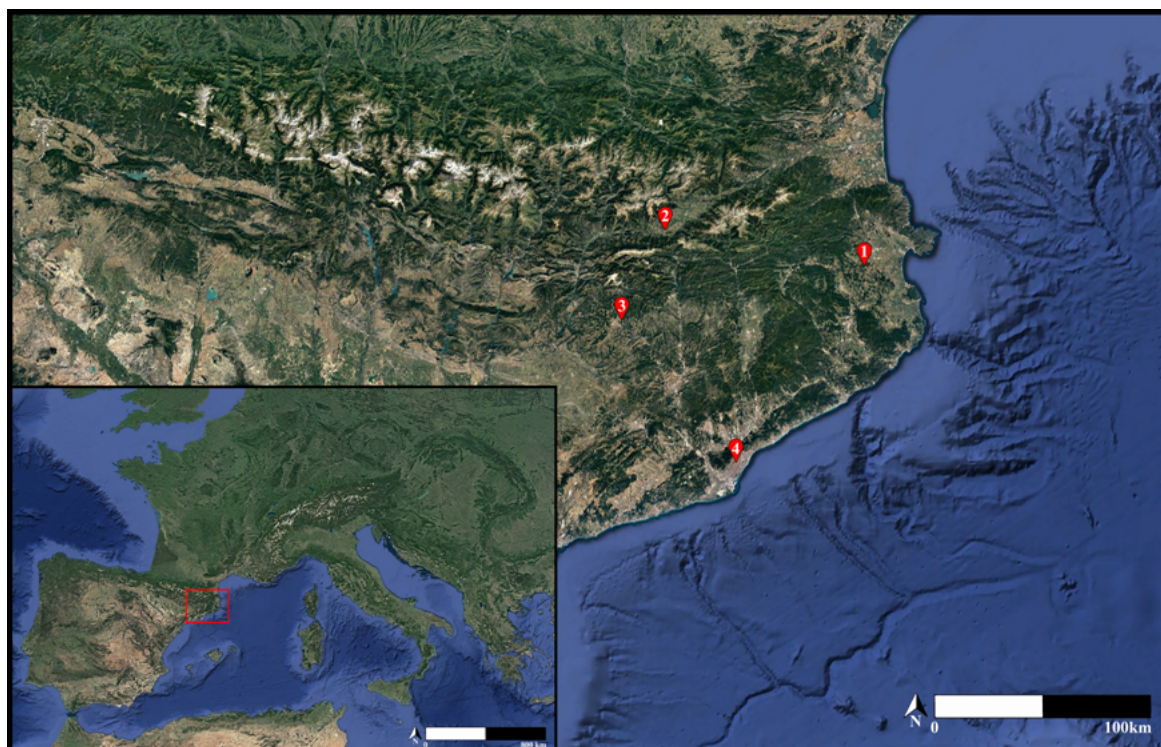


Figure 4.6 Geographical positions of the four archaeological sites included in this research: (1) Mas Castellar de Pontós, (2) Tossal de Baltarga, (3) Sant Esteve d'Olius, and (4) Turó de la Rovira (Google Earth Pro modified).

as a commercial enclave for cereal production, as well as a reserve centre for the *Emporion* area (Bouso *et al.* 2000; Fuertes *et al.* 2002). The anthracological analyses carried out at the Mas Castellar de Pontós site indicate the existence of mixed holm oak and sessile oak woodlands (*Quercus ilex* and *Quercus petraea*) in the area around the rural establishment, with the presence in addition of juniper (*Juniperus* sp.) and silver fir (*Abies alba*). Moreover, an ecosystem of riparian vegetation (*Alnus* and *Ulmus*) is attested, characteristic of the marshy Empordà plain, rich in ponds and wetlands (Ros and Piqué 2002). Carpological data provide evidence of a great variety of crops, both winter varieties (wheat and emmer) and spring types (millet, foxtail millet, barley, oats). Barley and millet are predominant, with the latter being the only C_4 plant, along with foxtail millet, present in the settlement. These cereal crops are combined, in

minor quantities, with the cultivation of legumes (pea, lentil), which are important not only for nitrogen fixation in the soil, maintaining a high level of fertility, but also for their high protein content. Among fruits, vines and, to a lesser extent, olive trees are present (Canal 2000; Canal 2002). Cereal production probably involved diverse strategies for intensive crop management, including both rotation systems (biennial and triennial) and the joint sowing of different species, such as foxtail millet and barley (Alonso 2000; Canal 2000). The recovered fauna remains indicate a predominance of domestic species (99% of recorded remains). Among these, caprines are the most represented group (51%), with sheep predominating, followed by cattle and pigs. Hunting was an occasional activity with minimal impact on the diet (Colominas 2013a). However, the few remains of deer, wild boar, and rabbit confirm the

proximity of wooded areas mixed with pastures. Regarding sheep husbandry, the prevailing presence of adult and old individuals (Colominas 2008; Colominas 2013) alongside a bi-modulated reproduction pattern, with births occurring from winter to late spring and in autumn (Messana *et al.* 2023a), suggest the exploitation of secondary products (i.e., milk and wool) throughout the year.

Tossal de Baltarga (Bellver de Cerdanya, 1166 m a.s.l.) is situated on the top of a hill in the eastern Catalan Pyrenees. The main purpose of the settlement was to exercise territorial control over the communication routes, encompassing both land and the river Segre, that crossed the Cerdanya plain (Colominas *et al.* 2023). The site has revealed three different phases of occupation spanning from the late Bronze Age to the Republican Roman period (Morera 2017). During the Iron Age phase (4th - 3rd century B.C.) Tossal de Baltarga must have played a relevant social and economic role within the *Ceretan* population. Indeed, several residential and working buildings linked to a single production unit are attested (Morera 2017; Colominas *et al.* 2023). Towards the end of the 3rd century BC, the settlement was violently destroyed by fire (Morera 2017). The majority of the archaeobotanical and faunal remains recovered come from one of the buildings (G). Here, charcoal remains of *Pinus sylvestris/nigra*, the main *taxon*, along with *Albies alba*, and *Rosaceae/Maloideae* (Colominas *et al.* 2023) were collected. The carpological remains, although limited, attest to the presence of barley (*Hordeum vulgare*), wheat (*Triticum aestivum/durum/turgidum*), millet (*Panicum miliaceum*), and einkorn (*Triticum monococcum*). However, the highest number of macrobotanical remains corresponds to wild plants

(Colominas *et al.* 2023). These data are supported by the analysis of phytoliths, the majority of which are derived from monocotyledonous plants, particularly grasses and weeds of the Pooideae subfamily (Colominas *et al.* 2023). The Iberian period witnessed an increase in agricultural production in the Cerdanya plain, favoured by a generally dry climate complemented by abundant water sources (Morera 2017; Olesti and Mercadal 2017). Consequently, during the 3rd century B.C., Cerdanya likely appeared as a plain characterised by an agrarian landscape bordered by forest vegetation essentially consisting of coniferous forests (pine and silver fir), which occupied the mountain area. Building G provided the remains of four sheep, a goat, and, in a separate space, a horse. Consequently, partial or total controlled stabling of livestock would have taken place at Tossal de Baltarga (Morera *et al.* 2017). All individuals were sub-adults or adults at the time of death caused by the fire. The mortality profiles thus suggest an interest in the products derived from the animals during their lifetimes rather than exclusively for their meat (Colominas *et al.* 2023). The sequential stable oxygen isotope analyses performed on the molars of three of the sheep show that births at Tossal de Baltarga occurred between late winter and spring, over a relatively narrow timeframe (Messana *et al.* 2023a). It has been suggested that these births, concentrated in time, were the result of human manipulation to minimise the labour of caring for pregnant females and newborns and ensuring their survival (Messana *et al.* 2023a). Therefore, it is plausible that the community living in the settlement was also organized considering the management of different livestock tasks. Remains of cattle and pigs were recovered in other buildings, indicating their presence and exploitation within the settlement (Olesti *et al. submitted*).

The Sant Esteve d'Olius (Solsonès, 664 m a.s.l.) site was a small village located in the fertile *Lacetan* plain. Situated in the Pre-Pyrenees area, inland in the Catalan region, the settlement was placed on the highest point of a small promontory. The area was bordered by the river Cardener, the principal communication way to the coast (Asensio *et al.* 2003, 2008). The site was occupied during Medieval and Iron Age times. During the Iron Age phase (3rd c. BC), it emerged as a fortified settlement specialised in storing and managing cereal surpluses, with silo fields and residential buildings (Asensio *et al.* 2003; Chorén and Caldach 2006; López 2009). The silo field areas around the site outnumber and exceed the designated residential areas, suggesting that agricultural activities were pivotal and must have been a pole of attraction for the other surrounding communities. The expansive fertile plain irrigated by the river Cardener probably played a crucial role in the development of these agricultural activities (Asensio *et al.* 2008). Although these types of strategic nuclei specialised in crop cereal storage are well known along the Iberian Mediterranean coastal zones, they are exceptional in inland locations, as in the case of Sant Esteve d'Olius (López 2009). The archaeobotanical data from the silos revealed a significant production of cereal crops, especially the winter varieties: barley and, in less proportion, wheat and emmer; as well as some scarce evidence of leguminous plants, such as peas and lentils (López 2009). Among wild plants, species of the *Rubiaceae* family are the most frequently attested, including catchweed bedstraw or stickwilly (*Galium aparine*, *Galium* sp.), as well as woodruff (*Asperula* sp.) and white bedstraw (*Galium* cf. *mollugo*) in minor quantities. Weedy grasses associated with winter cereals, such as oats

(*Avena* sp.), darnel or ryegrass (*Lolium* cf. *temulentum* and *Lolium* sp.) and timothy (*Phelum* sp.) are also present, in addition to other pluvial weeds like *Lithospermum* sp. Furthermore, the archaeological record includes evidence of collected fruits, such as sloe berries (*Prunus spinosa*) and an acorn (*Quercus* sp.; López 2009). The zooarchaeological analysis reveals a predominance of domestic mammal remains. Caprine are prevalent, with sheep more frequent than goats, followed by pigs and cattle (Colominas 2013b). Hunting was a secondary activity with limited impact on the human diet. The presence of wildlife remains such as deer, badger, *Leporidae*, fox, beech marten, amphibians, and fish confirms the proximity of watercourses and a wetland environment and attests to the presence of wooded areas near the settlement. The mortality profiles of sheep indicate the exploitation of meat and, secondarily, wool and milk (Colominas 2013b). The lambing period, occurring between late winter and early summer, was prolonged compared to the natural one, indicating anthropogenic intervention (Messana *et al.* 2023a). Furthermore, at Sant Esteve d'Olius the aggregation to the flock is attested for at least one individual with external provenance (and possibly a second one; Messana *et al.* 2023b).

The *Laietan* fortified settlement of Turó de la Rovira (mid-3rd century BC – late 3rd/early 2nd century BC) is located in the Barcelona plain, at 262 m. a.s.l., on the top of a small promontory near the Mediterranean coast (Colominas i Roca 1954; Giner 2018). The settlement has been interpreted as a second-order village of the *Laietan* territory during the Iron Age, occupying a dominant position over the neighbouring minor centres (Giner 2018). Archaeological research has revealed a set of residential buildings on the southern slope and

two silo field areas concentrated on the two sides of the village. The settlement was also delimited by the construction of a wall (Giner 2018). Anthracological studies attested to the dominance of open-landscape areas around the site, with abundant remains of strawberry tree (*Arbutus unedo*), holm oak/kermes oak (*Quercus ilex/coccifera*), and heather (*Erica* sp.). Deforestation was intense, probably due to the presence of cultivated fields all around (Riera *et al.* 2020). Carpological data show agriculture with a predominance of wheat and barley, and, in minor quantities, legumes, grapes, and figs. Interestingly, the study also documents the presence, albeit testimonial, of millet (Riera *et al.* 2020). The majority of the faunal remains come from silos with similar chronology and whose content of archaeocarpological remains is homogeneous (Riera *et al.* 2020). Caprines are the most attested *taxon*, with sheep slightly more present than goats. They are followed by pigs and cattle and, in minor numbers, equids, dogs, and *Leporidae*. Among sheep, adults predominate, indicating their exploitation for meat and wool (Colominas 2019). Both the duration and lambing period, with births occurring between spring and summer, were the result of anthropogenic scheduling aimed at extending the natural birth cycle (Messana *et al.* 2023a). Finally, a type of short seasonal mobility along a low altitudinal gradient is attested for part of the flock (Messana *et al.* 2023b). Therefore, it seems possible that there was a differentiated management of the flock within the settlement.

2.2 Materials

2.2.1 Bone collagen samples

In this study, a total of 43 sheep (*Ovis aries*, Linnaeus, 1758) remains from the four studied sites were selected for stable carbon and nitrogen isotope

analyses. In addition to sheep, a range of other archaeological herbivorous and omnivorous *taxa* (goat, cattle, pigs, dogs, horses, rabbit, deer, badger, and chicken; NR 153), both domestic and wild, were also measured to establish the local $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic baseline. Information regarding species, anatomical element, and age at death of each specimen (NR 196) is reported in Table 4.5. Only remains certainly belonging to different individuals and having a reliable taxonomic determination were selected for this study, considering both laterality and estimated age at death. Only bones from sub-adult or adult individuals were sampled.

Osteological analyses followed the criteria elaborated by Zeder and Pilaar (2010) for teeth and by Boessneck (1969) and Zeder and Lapham (2010) for the post-cranial skeleton were applied to distinguish between goat and sheep. The discrimination between wild boar and domesticated pig was based on the dimensions of anatomical elements and the osteological reference collections of the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA). Age at death was estimated through the observation of the epiphyseal fusion of long bones, following the methodologies proposed by Barone (1976), and of tooth eruption (Hillson 2005) and wear stage, as described by Payne (1973).

2.2.2 Tooth enamel samples

Sequential carbon and oxygen isotope analyses were conducted on 31 lower molars (18 second molars and 13 third molars) belonging to 22 sheep. For nine of these individuals, both M_2 and M_3 were sampled. All the selected molars exhibit completely or almost fully formed crowns and early wear stages. The same molars have been analysed in two previous studies aimed at

Table 4.5 List of animal bone specimens (ID) sampled for bulk collagen analysis. Element and age category of sampled specimens, extraction yield (mg collagen/g bone), collagen carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope compositions, collagen carbon (%C) and nitrogen (%N) contents, and collagen carbon:nitrogen atomic ratio (C:N).

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}\text{C}$	%C	$\delta^{15}\text{N}$	%N	C:N
MC OVAR 11144	<i>Ovis aries</i>	Metapod	Adult	8.89	-20.94	43.38	5.80	15.44	3.3
MC OVAR 11146	<i>Ovis aries</i>	Metatarsus	Adult	13.77	-19.64	42.15	5.49	15.70	3.1
MC OVAR 11159	<i>Ovis aries</i>	Calcaneus	Adult	12.59	-19.95	35.70	5.65	12.89	3.2
MC OVAR 11216	<i>Ovis aries</i>	Astragalus	Adult	8.41	-21.42	41.49	6.71	15.03	3.2
MC OVAR 11217	<i>Ovis aries</i>	Tibia	Adult	10.77	-19.40	41.68	5.40	15.19	3.2
MC OVAR 20129	<i>Ovis aries</i>	Phalanx I	Adult	15.81	-21.03	33.80	4.85	13.29	3.0
MC OVAR 20158	<i>Ovis aries</i>	Tibia	Adult	6.88	-20.29	43.51	4.85	15.38	3.3
MC OVAR 20160	<i>Ovis aries</i>	Mandible	Adult	7.19	-19.91	38.65	8.24	14.19	3.2
MC OVAR 20165	<i>Ovis aries</i>	Mandible	Adult	14.66	-19.75	38.96	5.53	15.08	3.0
MC OVAR 20168	<i>Ovis aries</i>	Humerus	Adult	14.40	-19.80	46.84	3.88	16.83	3.2
MC OVAR 100031	<i>Ovis aries</i>	Tibia	Adult	10.38	-20.10	40.71	6.70	14.84	3.2
BTB OVAR 3249.1	<i>Ovis aries</i>	Mandible	Adult	7.65	-20.27	36.58	5.61	13.70	3.1
BTB OVAR 3249.3	<i>Ovis aries</i>	Radius	Adult	7.09	-20.74	36.75	2.98	14.21	3.0
BTB OVAR 3249.4	<i>Ovis aries</i>	Radius	Adult	6.86	-20.77	35.03	5.34	13.29	3.1
BTB OVAR 3270.1	<i>Ovis aries</i>	Mandible	Adult	6.22	-19.76	37.41	4.89	13.31	3.3
BTB OVAR 3271.1	<i>Ovis aries</i>	Mandible	Subadult	6.75	-19.99	38.09	5.44	14.13	3.1
O OVAR 174	<i>Ovis aries</i>	Mandible	Adult	4.93	-20.65	38.35	5.19	13.93	3.2
O OVAR 227	<i>Ovis aries</i>	Tibia	Adult	2.92	-20.72	39.64	3.78	14.09	3.3
O OVAR 318	<i>Ovis aries</i>	Mandible	Adult	3.42	-20.01	36.65	6.54	13.58	3.1
O OVAR 339	<i>Ovis aries</i>	Tibia	Adult	11.59	-20.16	42.22	4.87	15.86	3.1
O OVAR 348	<i>Ovis aries</i>	Mandible	Adult	16.65	-20.43	44.87	4.32	16.14	3.2
O OVAR 361	<i>Ovis aries</i>	Humerus	Adult	29.82	-20.59	42.04	5.40	15.29	3.2
O OVAR 379	<i>Ovis aries</i>	Humerus	Adult	2.07	-20.52	31.71	4.52	12.38	3.0
O OVAR 385	<i>Ovis aries</i>	Mandible	Adult	6.29	-20.14	36.70	3.64	13.42	3.2
O OVAR 387	<i>Ovis aries</i>	Metacarpus	Adult	4.56	-20.08	34.42	4.29	12.85	3.1
O OVAR 397	<i>Ovis aries</i>	Metatarsus	Adult	7.01	-20.24	40.38	7.06	13.57	3.5
O OVAR 405	<i>Ovis aries</i>	Mandible	Adult	6.29	-20.27	35.62	4.69	12.39	3.4
O OVAR 438	<i>Ovis aries</i>	Radius	Adult	3.35	-20.88	32.76	3.04	13.14	2.9
O OVAR 452	<i>Ovis aries</i>	Metacarpus	Adult	13.45	-20.34	44.85	6.50	16.78	3.1
O OVAR 478	<i>Ovis aries</i>	Mandible	Adult	4.12	-19.44	32.20	5.28	12.73	3.0
O OVAR 484	<i>Ovis aries</i>	Mandible	Adult	14.26	-18.70	43.45	8.21	15.49	3.3
O OVAR 496	<i>Ovis aries</i>	Metatarsus	Adult	15.99	-20.85	33.71	6.77	12.04	3.3
O OVAR 500	<i>Ovis aries</i>	Radius	Adult	9.95	-22.11	40.29	4.49	14.25	3.3
TR OVAR 415.1	<i>Ovis aries</i>	Mandible	Adult	1.08	-19.70	32.97	4.73	13.26	2.9
TR OVAR 415.2	<i>Ovis aries</i>	Mandible	Adult	2.94	-20.25	35.20	7.76	11.96	3.4

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
TR OVAR 439	<i>Ovis aries</i>	Tibia	Adult	2.22	-20.54	36.80	4.63	13.93	3.1
TR OVAR 465	<i>Ovis aries</i>	Mandible	Adult	12.39	-20.15	43.15	6.58	16.04	3.1
TR OVAR 707	<i>Ovis aries</i>	Tibia	Adult	10.35	-20.07	41.48	4.59	14.69	3.3
TR OVAR 725	<i>Ovis aries</i>	Mandible	Adult	11.82	-20.58	42.22	5.09	15.75	3.1
TR OVAR 763	<i>Ovis aries</i>	Mandible	Adult	5.54	-19.72	38.95	8.21	13.24	3.4
TR OVAR 819	<i>Ovis aries</i>	Radius	Adult	10.92	-17.91	38.23	6.86	13.06	3.4
TR OVAR 831	<i>Ovis aries</i>	Mandible	Adult	2.49	-18.76	34.70	7.46	13.37	3.0
TR OVAR 1035	<i>Ovis aries</i>	Metatarsus	Adult	5.82	-20.31	32.20	5.38	11.22	3.3
MC CAHI 11144	<i>Capra hircus</i>	Mandible	Adult	10.28	-20.16	38.71	5.05	14.75	3.1
MC CAHI 20160	<i>Capra hircus</i>	Mandible	Adult	16.50	-20.50	40.97	4.57	14.71	3.2
MC CAHI 20162	<i>Capra hircus</i>	Humerus	Adult	14.11	-19.97	42.53	5.04	15.08	3.3
MC CAHI 100030	<i>Capra hircus</i>	Tibia	Adult	4.51	-20.40	29.30	3.60	10.73	3.2
BTB CAHI 3250.1	<i>Capra hircus</i>	Mandible	Subadult	10.86	-19.74	37.50	6.27	13.44	3.3
O CAHI 181	<i>Capra hircus</i>	Metacarpus	Adult	8.62	-20.06	39.61	4.93	14.21	3.3
O CAHI 186	<i>Capra hircus</i>	Mandible	Adult	4.11	-20.28	38.01	4.36	12.80	3.5
O CAHI 294	<i>Capra hircus</i>	Tibia	Adult	15.72	-19.91	44.05	5.81	15.54	3.3
O CAHI 297	<i>Capra hircus</i>	Phalanx I	Adult	19.05	-20.01	23.22	4.65	7.59	3.6
O CAHI 309	<i>Capra hircus</i>	Phalanx I	Adult	10.88	-20.42	42.67	3.34	15.63	3.2
O CAHI 403	<i>Capra hircus</i>	Phalanx I	Adult	17.65	-19.78	43.03	3.64	15.95	3.1
O CAHI 423	<i>Capra hircus</i>	Phalanx I	Adult	17.08	-20.53	41.25	3.31	15.02	3.2
O CAHI 496	<i>Capra hircus</i>	Humerus	Adult	7.24	-19.43	30.67	5.32	10.68	3.4
TR CAHI 707	<i>Capra hircus</i>	Mandible	Adult	4.49	-20.59	31.73	7.54	12.01	3.1
TR CAHI 719	<i>Capra hircus</i>	Mandible	Adult	5.17	-19.97	35.15	3.14	13.08	3.1
TR CAHI 726	<i>Capra hircus</i>	Phalanx I	Adult	15.31	-19.51	39.03	4.29	15.90	2.9
TR CAHI 729	<i>Capra hircus</i>	Humerus	Adult	16.50	-18.49	43.05	4.33	15.93	3.2
TR CAHI 739	<i>Capra hircus</i>	Mandible	Adult	10.69	-20.62	44.00	8.48	15.45	3.3
TR CAHI 748	<i>Capra hircus</i>	Phalanx I	Adult	18.33	-20.19	34.14	3.24	13.82	2.9
TR CAHI 805	<i>Capra hircus</i>	Mandible	Adult	5.70	-20.19	40.26	2.20	15.06	3.1
TR CAHI 821	<i>Capra hircus</i>	Phalanx I	Adult	15.39	-19.73	43.71	4.16	15.58	3.3
TR CAHI 10004	<i>Capra hircus</i>	Astragalus	Adult	101.36	-20.31	35.87	4.84	11.97	3.5
BTB O/C 3051	<i>Ovis vel Capra</i>	Humerus	Adult	9.39	-19.72	42.13	7.20	15.00	3.3
BTB O/C 3073	<i>Ovis vel Capra</i>	Tibia	Adult	6.04	-20.01	40.43	7.92	15.04	3.1
BTB O/C 3099	<i>Ovis vel Capra</i>	Tibia	Adult	16.02	-20.24	41.65	5.08	16.03	3.0
BTB O/C 3159	<i>Ovis vel Capra</i>	Ulna	Adult	15.72	-20.74	44.44	4.53	16.49	3.1
MC BOTA 11125	<i>Bos taurus</i>	Mandible	Adult	9.51	-18.86	38.35	5.84	14.22	3.1

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
MC BOTA 11145	<i>Bos taurus</i>	Metacarpus	Adult	7.75	-20.69	41.31	5.36	15.02	3.2
MC BOTA 11150	<i>Bos taurus</i>	Mandible	Adult	11.61	-18.42	41.18	5.37	15.26	3.1
MC BOTA 20162	<i>Bos taurus</i>	Tibia	Adult	6.70	-19.96	44.18	6.48	16.76	3.1
MC BOTA 20168	<i>Bos taurus</i>	Radius	Adult	6.00	-19.24	44.43	5.20	15.59	3.3
MC BOTA 100030	<i>Bos taurus</i>	Phalanx I	Adult	8.15	-18.30	33.72	5.80	12.47	3.2
BTB BOTA 3031	<i>Bos taurus</i>	Mandible	Adult	17.12	-20.43	40.60	3.40	15.16	3.1
BTB BOTA 3051	<i>Bos taurus</i>	Mandible	Adult	9.29	-20.74	34.80	5.55	13.00	3.1
BTB BOTA 3064	<i>Bos taurus</i>	Phalanx II	Adult	14.09	-20.93	40.61	7.57	16.10	2.9
O BOTA 142	<i>Bos taurus</i>	Tibia	Adult	11.76	-20.19	41.92	4.72	15.47	3.2
O BOTA 181	<i>Bos taurus</i>	Tibia	Adult	10.59	-21.20	41.47	3.31	14.72	3.3
O BOTA 195	<i>Bos taurus</i>	Metacarpus	Adult	6.62	-20.95	39.60	4.70	14.62	3.2
O BOTA 205	<i>Bos taurus</i>	Radius	Adult	4.19	-20.71	31.82	4.65	11.21	3.3
O BOTA 318	<i>Bos taurus</i>	Humerus	Adult	12.41	-20.34	43.84	5.79	15.10	3.4
O BOTA 320	<i>Bos taurus</i>	Humerus	Adult	1.86	-20.42	32.58	4.90	11.95	3.2
O BOTA 329	<i>Bos taurus</i>	Radius	Adult	16.43	-20.29	35.78	3.72	13.18	3.2
O BOTA 349	<i>Bos taurus</i>	Ulna	Adult	7.16	-20.70	36.98	3.46	13.62	3.2
O BOTA 381	<i>Bos taurus</i>	Tibia	Adult	10.47	-20.56	42.71	2.81	15.55	3.2
O BOTA 387	<i>Bos taurus</i>	Tibia	Adult	20.83	-22.64	41.41	4.69	15.03	3.2
O BOTA 394	<i>Bos taurus</i>	Tibia	Adult	10.90	-20.45	41.12	5.98	15.02	3.2
O BOTA 397	<i>Bos taurus</i>	Metatarsus	Adult	3.72	-20.28	28.30	6.92	9.23	3.6
O BOTA 399	<i>Bos taurus</i>	Radius	Adult	17.77	-21.32	42.52	4.04	15.25	3.3
O BOTA 423	<i>Bos taurus</i>	Humerus	Adult	16.51	-20.14	40.22	4.52	14.35	3.3
O BOTA 448	<i>Bos taurus</i>	Humerus	Adult	14.06	-21.78	36.92	1.92	12.93	3.3
O BOTA 482	<i>Bos taurus</i>	Metatarsus	Adult	10.42	-20.14	43.32	6.98	15.18	3.3
TR BOTA 412	<i>Bos taurus</i>	Femur	Adult	4.60	-21.14	37.45	4.92	14.25	3.1
TR BOTA 415	<i>Bos taurus</i>	Phalanx I	Adult	38.43	-20.63	35.34	3.83	13.50	3.1
TR BOTA 439	<i>Bos taurus</i>	Metatarsus	Adult	18.98	-21.43	46.76	4.22	17.76	3.1
TR BOTA 707	<i>Bos taurus</i>	Metacarpus	Adult	11.17	-20.52	42.43	3.60	16.29	3.0
TR BOTA 715	<i>Bos taurus</i>	Metatarsus	Adult	5.66	-19.40	39.03	4.80	15.01	3.0
TR BOTA 719	<i>Bos taurus</i>	Mandible	Adult	10.18	-19.47	41.24	6.90	15.55	3.1
TR BOTA 725	<i>Bos taurus</i>	Ulna	Adult	11.91	-20.38	40.20	6.70	15.08	3.1
TR BOTA 729	<i>Bos taurus</i>	Tibia	Adult	5.23	-18.84	38.72	7.12	14.09	3.2
TR BOTA 739	<i>Bos taurus</i>	Tibia	Adult	11.36	-21.00	44.06	2.08	16.47	3.1
TR BOTA 1035	<i>Bos taurus</i>	Metacarpus	Adult	4.55	-20.19	34.97	6.22	13.25	3.1
MC SUDO 11218	<i>Sus domesticus</i>	Cranium	Adult	7.15	-18.62	38.31	6.92	13.86	3.2

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
MC SUDO 20158	<i>Sus domesticus</i>	Mandible	Adult	17.95	-20.39	36.24	5.40	14.02	3.0
MC SUDO 20168	<i>Sus domesticus</i>	Mandible	Adult	14.84	-19.59	43.23	5.51	16.59	3.0
MC SUDO 100033	<i>Sus domesticus</i>	Ulna	Adult	11.28	-20.50	42.20	4.30	15.34	3.2
BTB SUDO 3029	<i>Sus domesticus</i>	Mandible	Adult	6.91	-20.18	40.25	5.61	15.29	3.1
BTB SUDO 3051	<i>Sus domesticus</i>	Mandible	Adult	5.96	-20.14	40.94	8.43	15.28	3.1
O SUDO 186	<i>Sus domesticus</i>	Mandible	Adult	5.85	-19.80	37.01	6.32	12.23	3.5
O SUDO 205	<i>Sus domesticus</i>	Mandible	Adult	3.86	-20.25	35.22	4.42	12.58	3.3
O SUDO 235	<i>Sus domesticus</i>	Radius	Adult	6.46	-20.27	38.24	4.20	13.59	3.3
O SUDO 245	<i>Sus domesticus</i>	Mandible	Adult	8.52	-20.45	40.88	7.83	14.14	3.4
O SUDO 309	<i>Sus domesticus</i>	Tibia	Adult	5.92	-20.42	37.63	10.18	12.57	3.5
O SUDO 311	<i>Sus domesticus</i>	Mandible	Adult	1.28	-20.32	31.85	4.00	12.51	3.0
O SUDO 318	<i>Sus domesticus</i>	Tibia	Adult	14.94	-20.32	43.20	6.24	14.67	3.4
O SUDO 329	<i>Sus domesticus</i>	Maxilla	Adult	9.24	-19.94	39.31	8.50	14.06	3.3
O SUDO 371	<i>Sus domesticus</i>	Calcaneus	Adult	6.36	-20.61	40.90	7.03	15.02	3.2
O SUDO 385.1	<i>Sus domesticus</i>	Mandible	Adult	4.89	-20.96	38.12	7.69	13.67	3.3
O SUDO 385.2	<i>Sus domesticus</i>	Mandible	Subadult	6.21	-20.55	37.96	5.51	14.23	3.1
O SUDO 397	<i>Sus domesticus</i>	Mandible	Adult	14.48	-20.80	43.49	4.08	15.91	3.2
O SUDO 399	<i>Sus domesticus</i>	Maxilla	Adult	37.35	-20.03	36.71	4.33	13.81	3.1
O SUDO 427	<i>Sus domesticus</i>	Calcaneus	Adult	21.19	-20.78	34.97	5.72	13.26	3.1
O SUDO 482	<i>Sus domesticus</i>	Mandible	Adult	3.52	-20.34	38.22	7.12	14.87	3.0
O SUDO 486	<i>Sus domesticus</i>	Ulna	Adult	6.85	-20.07	38.18	5.56	14.13	3.2
TR SUDO 415	<i>Sus domesticus</i>	Humerus	Adult	3.52	-20.88	37.74	6.79	14.15	3.1
TR SUDO 465	<i>Sus domesticus</i>	Metapod	Adult	14.19	-20.39	42.01	6.16	15.60	3.1
TR SUDO 707	<i>Sus domesticus</i>	Humerus	Adult	6.20	-19.56	37.55	4.80	14.14	3.1
TR SUDO 725	<i>Sus domesticus</i>	Mandible	Adult	8.50	-20.32	41.28	6.19	14.60	3.3
TR SUDO 739	<i>Sus domesticus</i>	Mandible	Adult	4.90	-20.27	27.97	5.68	9.36	3.5
TR SUDO 748	<i>Sus domesticus</i>	Metapod	Adult	11.32	-20.30	41.62	6.20	15.39	3.2
TR SUDO 765	<i>Sus domesticus</i>	Metapod	Adult	12.70	-20.55	41.94	4.67	15.30	3.2
TR SUDO 766	<i>Sus domesticus</i>	Scapula	Adult	8.00	-20.50	40.54	7.09	14.22	3.3
TR SUDO 821	<i>Sus domesticus</i>	Metapod	Adult	13.10	-20.80	41.68	5.14	15.98	3.0
TR SUDO 1065	<i>Sus domesticus</i>	Metapod	Adult	5.46	-20.76	41.07	4.36	15.65	3.1
MC EQCA 11123	<i>Equus caballus</i>	Metatarsus	Adult	5.06	-18.94	26.69	5.33	9.58	3.2
MC EQCA 11159	<i>Equus caballus</i>	Phalanx I	Adult	5.92	-21.61	37.70	5.87	14.29	3.1
MC EQCA 20160	<i>Equus caballus</i>	Phalanx II	Adult	4.68	-19.63	30.26	4.96	11.16	3.2
MC EQCA 20165	<i>Equus caballus</i>	Tibia	Adult	10.78	-20.03	40.83	5.76	15.07	3.2

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
MC EQCA 20168	<i>Equus caballus</i>	Humerus	Adult	11.83	-19.87	44.75	5.13	17.07	3.1
O EQCA 148	<i>Equus caballus</i>	Scapula	Adult	12.08	-21.40	30.26	1.82	10.48	3.4
O EQCA 397	<i>Equus caballus</i>	Mandible	Adult	2.57	-21.07	33.35	6.97	11.69	3.3
TR EQCA 415	<i>Equus caballus</i>	Mandible	Adult	14.11	-20.36	43.34	3.42	16.89	3.0
TR EQCA 439	<i>Equus caballus</i>	Pelvis	Adult	14.71	-20.42	42.47	4.32	14.71	3.4
TR EQCA 729	<i>Equus caballus</i>	Humerus	Adult	6.82	-21.71	41.15	3.73	15.87	3.0
TR EQCA 805	<i>Equus caballus</i>	Femur	Adult	4.00	-19.19	38.70	6.63	14.39	3.1
TR EQCA 1037	<i>Equus caballus</i>	Mandible	Adult	3.88	-18.67	37.79	4.33	14.72	3.0
O CEEL 205	<i>Cervus elaphus</i>	Phalanx I	Adult	11.58	-20.24	42.05	2.15	16.01	3.1
O CEEL 245	<i>Cervus elaphus</i>	Tibia	Adult	11.32	-21.04	42.64	3.27	14.87	3.3
O CEEL 309	<i>Cervus elaphus</i>	Metatarsus	Adult	9.45	-21.65	41.18	3.41	14.90	3.2
O CEEL 339	<i>Cervus elaphus</i>	Metatarsus	Adult	14.71	-21.07	37.97	4.66	13.18	3.4
O CEEL 387	<i>Cervus elaphus</i>	Radius	Adult	12.49	-20.71	43.16	3.49	15.47	3.3
O CEEL 421	<i>Cervus elaphus</i>	Phalanx I	Adult	9.43	-21.08	40.36	3.40	14.56	3.2
O CEEL 452	<i>Cervus elaphus</i>	Phalanx I	Adult	64.80	-21.73	42.04	3.28	15.47	3.2
MC CAFA 12028.1	<i>Canis familiaris</i>	Humerus	Adult	9.16	-19.72	41.60	6.79	15.30	3.2
MC CAFA 12028.2	<i>Canis familiaris</i>	Humerus	Adult	9.58	-20.47	38.83	5.61	14.30	3.2
MC CAFA 12028.3	<i>Canis familiaris</i>	Ulna	Adult	9.16	-16.97	39.99	5.94	15.16	3.1
MC CAFA 20165	<i>Canis familiaris</i>	Mandible	Adult	17.92	-18.25	42.17	7.27	15.53	3.2
MC CAFA 100031	<i>Canis familiaris</i>	Metacarpus	Adult	4.29	-17.50	33.70	8.40	12.62	3.1
O CAFA 349	<i>Canis familiaris</i>	Ulna	Adult	12.52	-19.19	41.71	5.27	15.37	3.2
TR CAFA 415	<i>Canis familiaris</i>	Radius	Adult	1.98	-19.98	15.45	8.21	5.38	3.3
TR CAFA 719	<i>Canis familiaris</i>	Metapod	Adult	9.27	-18.32	37.00	10.07	12.64	3.4
TR CAFA 726	<i>Canis familiaris</i>	Pelvis	Adult	6.67	-20.09	37.83	7.85	14.55	3.0
TR CAFA 766	<i>Canis familiaris</i>	Metapod	Adult	15.70	-20.15	40.45	7.15	14.28	3.3
TR CAFA 819	<i>Canis familiaris</i>	Metapod	Adult	10.13	-19.66	42.12	8.83	15.62	3.1
O MEME 257	<i>Meles meles</i>	Tibia	Adult	7.08	-18.64	41.84	7.14	15.05	3.2
MC AV 11221	<i>Milvus milvus</i>	Humerus	Adult	24.74	-18.20	40.76	7.42	14.67	3.2
MC AV 11145	Bird	Ulna	Adult	14.46	-21.30	41.71	6.11	16.33	3.0
MC AV 20158	Bird	Radius	Adult	18.06	-20.81	41.28	6.74	14.40	3.3
O AV 186.1	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult	15.25	-18.92	44.25	7.27	15.59	3.3
O AV 186.2	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult	16.88	-18.45	43.25	7.98	16.25	3.1
O AV 205	<i>Gallus gallus</i>	Tibia-Tarsus	Adult	12.18	-19.43	42.43	8.15	14.57	3.4
O AV 361	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult	9.98	-18.88	35.46	8.23	12.95	3.2
O AV 387	<i>Gallus gallus</i>	Tibia-Tarsus	Adult	12.07	-19.56	34.52	7.29	12.52	3.2

Sample ID	Taxa	Element	Age Category	Yield (mg/g)	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
TR AV 528.1	<i>Gallus gallus</i>	Humerus	Adult	9.79	-19.51	42.72	8.59	15.92	3.1
TR AV 528.2	<i>Gallus gallus</i>	Humerus	Adult	15.92	-20.03	32.85	9.82	12.24	3.1
TR AV 719	<i>Gallus gallus</i>	Tarsus-Metatarsus	Adult	12.42	-19.76	40.83	9.21	15.92	3.0
TR AV 763	<i>Gallus gallus</i>	Femur	Adult	13.14	-20.54	45.00	7.44	16.61	3.2
TR AV 764.1	<i>Gallus gallus</i>	Tibia-Tarsus	Adult	11.35	-20.27	41.60	10.27	14.36	3.4
TR AV 764.2	<i>Gallus gallus</i>	Tibia-Tarsus	Adult	14.56	-20.58	47.87	7.26	17.20	3.2
TR AV 765	<i>Gallus gallus</i>	Tibia-Tarsus	Adult	12.10	-20.73	36.52	7.64	13.19	3.2
MC ORCU 20122	<i>Oryctolagus cuniculus</i>	Humerus	Adult	9.91	-21.54	39.72	3.08	14.07	3.3
MC ORCU 20158	<i>Oryctolagus cuniculus</i>	Pelvis	Adult	13.40	-21.52	43.26	3.76	16.07	3.1
MC ORCU 20160	<i>Oryctolagus cuniculus</i>	Radius	Adult	14.97	-22.05	40.27	5.34	14.77	3.2
MC ORCU 20162	<i>Oryctolagus cuniculus</i>	Radius	Adult	16.53	-21.56	41.24	3.45	15.50	3.1
MC ORCU 20165.1	<i>Oryctolagus cuniculus</i>	Ulna	Adult	13.68	-21.14	41.88	3.95	15.41	3.2
MC ORCU 20165.2	<i>Oryctolagus cuniculus</i>	Ulna	Adult	11.66	-21.15	42.37	3.76	15.84	3.1
O ORCU 381	<i>Oryctolagus cuniculus</i>	Tibia	Adult	10.66	-21.43	35.35	9.42	12.31	3.4
O ORCU 397	<i>Oryctolagus cuniculus</i>	Tibia	Adult	13.45	-21.97	42.04	1.99	15.11	3.2
O ORCU 459	<i>Oryctolagus cuniculus</i>	Tibia	Adult	13.34	-22.94	34.31	4.38	12.70	3.2
O ORCU 486.1	<i>Oryctolagus cuniculus</i>	Tibia	Adult	13.06	-22.48	40.70	8.18	14.71	3.2
O ORCU 486.2	<i>Oryctolagus cuniculus</i>	Tibia	Adult	13.91	-19.65	41.41	5.66	15.75	3.1
TR ORCU 439	<i>Oryctolagus cuniculus</i>	Pelvis	Subadult	6.30	-21.61	34.14	6.79	13.38	3.0
TR ORCU 463	<i>Oryctolagus cuniculus</i>	Humerus	Adult	10.76	-20.27	40.72	4.31	15.13	3.1
TR ORCU 739	<i>Oryctolagus cuniculus</i>	Metapod	Adult	5.97	-21.93	31.30	9.97	11.69	3.1

Table 4.6 Sheep tooth specimens (ID) sampled for the sequential carbon and oxygen analyses in this study: site, side (L, left; R, right), wear stages and estimated age of death according to S. Payne (1973); na, no analysed.

Site	Teeth ID	Side	M ₂		M ₃	
			Wear stage	Age estimation	Wear stage	Age estimation
Mas Castellar de Pontós (MC)	11144	L	F	2-6 years	na	na
	12023	L	E	2-3 years	na	na
	20102	L	E	2-3 years	na	na
	20160	R	E	2-3 years	F	3-4 years
	20165	R	F	3-4 years	F	3-4 years
	11132	R	na	na	G	4-6 years
	11134	L	na	na	G	4-6 years
	11138	L	na	na	G	4-6 years
Tossal de Baltarga (BTB)	3249	R	E	2-3 years	na	na
	3270	R	F	3-4 years	F	3-4 years
	3271	L	D	21-24 months	na	na
	3031	L	na	na	F	3-4 years
Sant Esteve d'Olius (O)	174	L	E	2-3 years	na	na
	205	R	E	2-3 years	E	2-3 years
	318	R	G	4-5 years	G	4-5 years
	348	R	F	4-6 years	na	na
	478	L	E	2-3 years	E	2-3 years
	482	R	F	4-6 years	na	na
	484	R	F	4-6 years	na	na
Turó de la Rovira (TR)	725	R	F	3-4 years	F	3-4 years
	763	L	F	3-4 years	F	3-4 years
	831	L	E	2-3 years	E	2-3 years

investigating the reproduction patterns and mobility strategies adopted by Iberian populations during the Middle/Late Iron Age (Messana *et al.* 2023a, 2023b). Table 4.6 provides descriptive information (side, wear stage, and estimated age of death) about the teeth selected for this study.

2.3 Methods

2.3.1 Bone collagen extraction and carbon and nitrogen isotope analyses

Sample preparation and collagen extraction were performed at the Biomarkers Laboratory of the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA). A small fragment of bone was cut and removed from each specimen using a Dremel diamond rotating wheel. The surface of the bone shards was cleaned by abrasion with a tungsten drill to remove any visible contaminants.

Collagen extraction followed the protocol proposed by Longin (1971) and modified by Bocherens *et al.* (1991). The bone fragments were initially soaked in 0.5 M HCl for demineralisation, rinsed several times with distilled water, and soaked in NaOH (0.125 M) for 20 hours to remove potential organic contaminants. After another round of rinsing, the samples were diluted and gelatinised with 0.01 M HCl at 100°C for 17 hours (pH 2). Finally, collagen samples were microfiltered using 5 µm filters to remove any residues and subsequently frozen. Samples were lyophilised at the Institut de Ciència i Tecnologia Ambientals (ICTA-UAB). Gelatin-collagen samples weighing about 300 µm were set into tin capsules and analysed at the Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), using a Thermo Flash 1112 elemental analyser (EA) coupled to a Thermo

Delta V Advantage isotope ratio mass spectrometer (IRMS) with a ConFlo III interface. The mean analytical precision was verified using the international standard laboratory IAEA 600 (caffeine; theoretical values: $\delta^{13}\text{C} = -27.77 \pm 0.04\text{‰}$, $\delta^{15}\text{N} = +1.0 \pm 0.2\text{‰}$) and used for data calibration. The average analytical error was $<0.05\text{‰}$ (1σ) for $\delta^{13}\text{C}$ and $\pm 0.13\text{‰}$ $\delta^{15}\text{N}$, determined within each run and from repeated measurements of the standard. The isotope ratios are reported for carbon as $\delta^{13}\text{C}$ Vienna Pee Dee Belemnite (V-PDB) and for nitrogen as $\delta^{15}\text{N}$ atmospheric nitrogen (AIR): $\chi \times 1000\text{‰}$, where χ stands for ^{13}C or ^{15}N and R stands for $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$. To evaluate the reliability of the isotopic signature of the collagen extracts, several quality criteria were applied: a yield of extraction $\geq 10 \text{ mg}\cdot\text{g}^{-1}$, percentages of C $\geq 30\%$ and N $\geq 10\%$, and a range of atomic C:N ratio between 2.9 and 3.6 (DeNiro 1985; Ambrose 1990; Van Klinken 1999).

To test the statistical significance of the isotopic data we use the ANOVA and Kruskal-Wallis tests with Past (4.03), setting the significance p value at <0.05 .

2.3.2 Sequential carbon and oxygen isotope analysis

Before sampling, the surface of the selected teeth was cleaned by abrasion with a tungsten drill. Subsequently, enamel bands were sequentially sampled with a diamond drill on the buccal surface, on the distal lobe of M_2 and on the central lobe of M_3 . Samples were taken at 1-2 mm intervals from the apex to the enamel-root junction (ERJ) of each tooth. The positions of the sample bands were recorded in millimetres along the entire crown, starting from the ERJ. The drilling and the chemical treatment of the samples were performed at the Biomarkers Laboratory of the Institut Català de

Paleoecologia Humana i Evolució Social (IPHES-CERCA). A total of 473 enamel powder samples (between 10 and 20 samples per tooth) were collected, weighing between 2.5 and 13.7 mg. Following the protocol described by Balasse *et al.* (2002) and modified by Tornero *et al.* (2013), the bioapatite samples were treated to remove exogenous carbonate contamination (4 hours in 0.1 M acetic acid [CH_3COOH]; 0.1 ml solution/mg sample), rinsed multiple times in distilled water and dried in an oven at 70°C for 48 hours. Once treated, samples were measured using an automated carbonate preparation device (KIEL-III) interfaced with a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Department of Geosciences), University of Arizona (USA), under the scientific supervision of Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C . To ensure the accuracy and precision of measurements, NBS-19 and NBS-18 international standards were utilized. The mean analytical precision within each run and from replicate measurements of standards during analysis varies $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.08\text{‰}$ for $\delta^{13}\text{C}$ (1σ). The isotope composition is reported in δ notation and expressed in per mil (‰), normalised to the Vienna-Pee Dee Belemnite (V-PDB) standard for carbon values.

3. Results

3.1 Collagen preservation and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis results

The carbon and nitrogen isotopic composition and collagen quality indicators of each individual are reported in Table 4.5. Collagen was successfully extracted from all samples analysed. The majority of the collagen

samples exhibit carbon and nitrogen content values and C:N ratios are in accordance with the quality criteria outlined in the literature (DeNiro 1985; Ambrose 1990; Van Klinken 1999). Collagen yields range from 1.08 to 101.36 mg/g. Only samples with a C:N ratio falling within the ranges of 2.9 to 3.5, wt% C >30, and wt% N >10 were considered for final interpretation. This led to the exclusion of six individuals: MC CAHI 100030, MC EQCA 11123, O CAHI 297, O BOTA 397, TR SUDO 739, and TR CAFA 415. The mean of the C:N ratios of the 190 samples is 3.2 ± 0.1 . The carbon content (in wt% C) exhibits a mean value of $39.4\% \pm 3.68\%$, whilst the nitrogen content (in wt% N) displays a mean value of $14.5\% \pm 1.39\%$.

The mean of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotope values of the faunal remains (corresponding to adult specimens) are $-20.3 \pm 0.91\text{‰}$ and $5.6 \pm 1.78\text{‰}$, respectively. All $\delta^{13}\text{C}$ values fall within the expected range for a diet primarily composed of C_3 plants. Likewise, all $\delta^{15}\text{N}$ values fit within the range for a diet encompassing both terrestrial plant and animal protein sources. The mean and range of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the samples analysed for every species at each site are illustrated in Figure 4.7.

Collagen samples from sheep from the four studied sites display a $\delta^{13}\text{C}$ mean value of $-20.2 \pm 0.71\text{‰}$ and a $\delta^{15}\text{N}$ mean value of $5.5 \pm 1.33\text{‰}$ (NR 43). Specifically, sheep from Mas Castellar de Pontós present a mean value of $-20.2 \pm 0.65\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.7 \pm 1.16\text{‰}$ in $\delta^{15}\text{N}$ (NR 11). Tossal de Baltarga sheep exhibit a mean value of $-20.3 \pm 0.45\text{‰}$ and one of $4.9 \pm 1.08\text{‰}$ in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ respectively (NR 5). Sant Esteve d'Olius provided a mean value of $-20.4 \pm 0.70\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.2 \pm 1.38\text{‰}$ in $\delta^{15}\text{N}$ among the analysed sheep (NR 17). Finally, sheep from Turó de la Rovira present

a $\delta^{13}\text{C}$ mean value of $-19.8 \pm 0.85\text{‰}$ and a $\delta^{15}\text{N}$ mean value of $6.1 \pm 1.40\text{‰}$ (NR 10). ANOVA and Kruskal-Wallis tests were conducted to assess potential differences in the mean and range of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values among the sheep samples from the four sites. The results revealed that there are no statistically significant differences between the sites for both the mean and the range of $\delta^{13}\text{C}$ values (ANOVA test: $F = 1.41$; $p = 0.2544$; Kruskal-Wallis tests: $H = 3.479$; $p = 0.3235$) and $\delta^{15}\text{N}$ values (ANOVA test: $F = 1.58$; $p = 0.209$; Kruskal-Wallis tests: $H = 4.192$; $p = 0.2414$). Comparison with results obtained from four sheep remains dated to the Roman imperial period (II-III AD) and recovered from the necropolis of the Vila de Madrid site (Barcelona) shows no substantial differences in either $\delta^{13}\text{C}$ (Kruskal-Wallis tests: $H = 4.025$; $p = 0.4025$) and $\delta^{15}\text{N}$ values (Kruskal-Wallis tests: $H = 4.172$; $p = 0.3831$; Salazar-García *et al.* 2022).

The mean results for the other *taxa* analysed are presented as follows. For *Capra hircus* (NR 20), the mean $\delta^{13}\text{C}$ value is $-20.0 \pm 0.50\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $4.7 \pm 1.51\text{‰}$; goats from Mas Castellar de Pontós display a mean value of $-20.21 \pm 0.27\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.89 \pm 0.27\text{‰}$ in $\delta^{15}\text{N}$ (NR 3); at Tossal de Baltarga, the only goat analysed exhibits a $\delta^{13}\text{C}$ value of -19.74‰ and a $\delta^{15}\text{N}$ value of 6.27‰ ; goats from Sant Esteve d'Olius have a mean value of $-20.06 \pm 0.39\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.39 \pm 1.00\text{‰}$ in $\delta^{15}\text{N}$ (NR 7); goats from Turó de la Rovira present a mean value of $-19.96 \pm 0.66\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.69 \pm 2.05\text{‰}$ in $\delta^{15}\text{N}$ (NR 9). There are no statistically significant differences in the mean and range of carbon and nitrogen values between the four sites. Comparisons can be made between the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the goat samples and those of two individuals from two

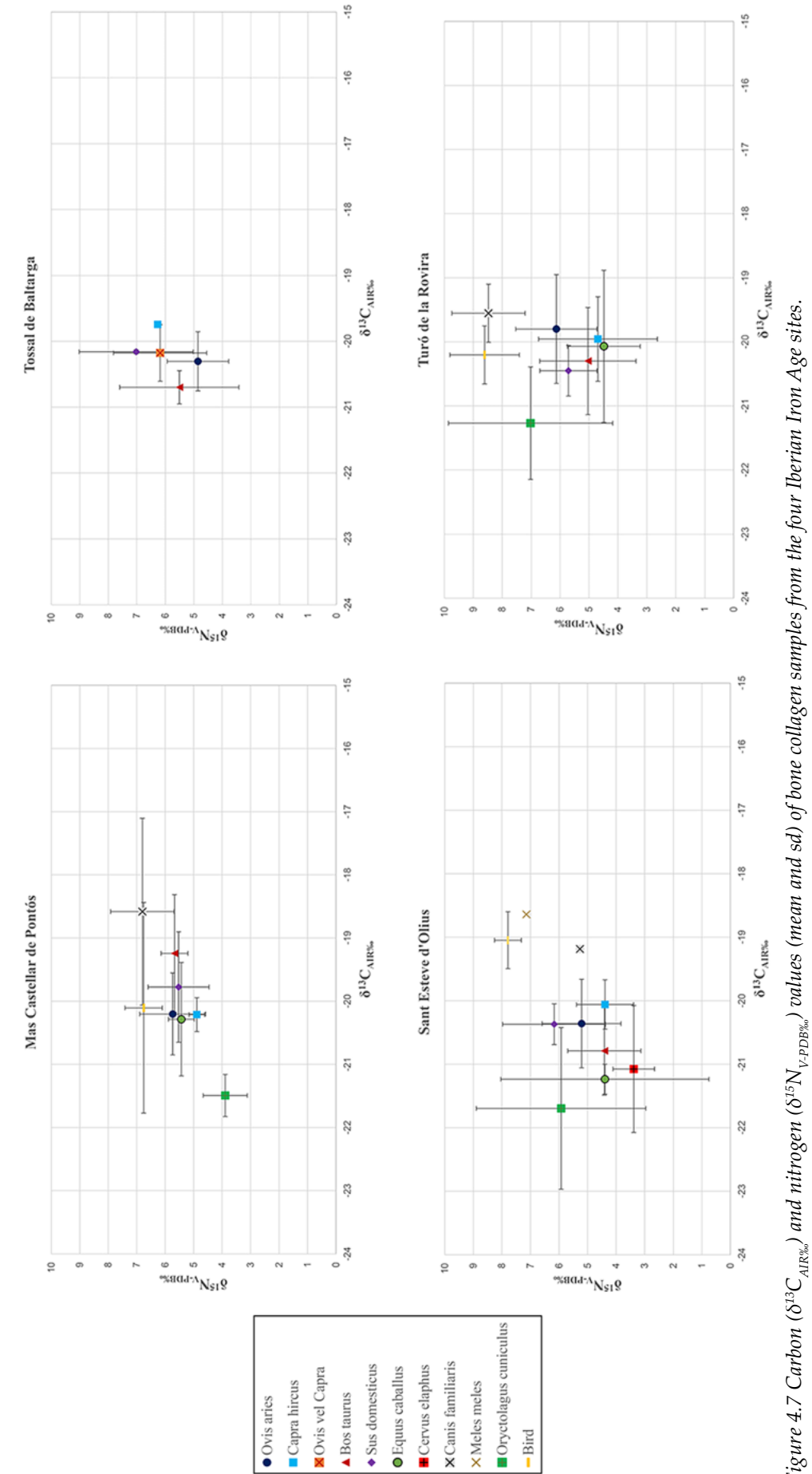


Figure 4.7 Carbon ($\delta^{13}C_{AIR\text{‰}}$) and nitrogen ($\delta^{15}N_{V-PDB\text{‰}}$) values (mean and sd) of bone collagen samples from the four Iberian Iron Age sites.

Catalan sites: Can Roqueta (Barcelona, 1900-16000 cal BC) and Minferri (Lleida, 2100-1650 cal BC), both dating to the Early and Middle Bronze Age. The current data indicates that there are no notable differences in the $\delta^{13}\text{C}$ (Kruskal-Wallis tests: $H = 4.684$; $p = 0.3207$) and $\delta^{15}\text{N}$ (Kruskal-Wallis tests: $H = 2.937$; $p = 0.5684$) values between these periods (Grandal-d'Anglade *et al.* 2019).

For *Bos taurus* (NR 35), the mean $\delta^{13}\text{C}$ value is $-20.3 \pm 0.93\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $5.0 \pm 1.45\text{‰}$; at Mas Castellar de Pontós cattle exhibit a mean value of $-19.26 \pm 0.85\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.90 \pm 0.74\text{‰}$ in $\delta^{15}\text{N}$ (NR 7); cattle from Tossal de Baltarga display a mean value of $-20.70 \pm 0.25\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.51 \pm 2.09\text{‰}$ in $\delta^{15}\text{N}$ (NR 3); individuals from Sant Esteve d'Olius show a mean value of $-20.79 \pm 0.70\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.41 \pm 1.28\text{‰}$ in $\delta^{15}\text{N}$ (NR 15); at Turó de la Rovira cattle have a mean value of $-20.30 \pm 0.84\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.04 \pm 1.67\text{‰}$ in $\delta^{15}\text{N}$ (NR 10). Among the four sites, a difference can be noted in the diet of individuals from Mas Castellar de Pontós, displaying low $\delta^{13}\text{C}$ values (mean value $-19.26\text{‰} \pm 0.85\text{‰}$) suggesting a slight integration of C_4 plants, in contrast to the predominantly C_3 diet of those from Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira (Kruskal-Wallis tests: $H = 10.95$; $p = 0.01199$). No statistically significant difference is observed in $\delta^{15}\text{N}$ values. The existing literature allows comparisons with various sites of proximate chronologies: Can Roqueta (different levels dated to E-MBA, LBA, EIA), Minferri (E-MB A), Vila de Madrid (RP), Carrer Ample 1 (RP). The five individuals from the E-MBA levels of Can Roqueta and the six individuals from the LBA levels show a mean $\delta^{13}\text{C}$ value of $-19.4 \pm 1.20\text{‰}$ and $-18.8 \pm 3.40\text{‰}$, respectively (Grandal-

d'Anglade *et al.* 2019; Albizuri *et al.* 2021). These data might suggest the integration of C_4 plants into their diet, contrasting with the results obtained for cattle from Tossal de Baltarga, Sant Esteve d'Olius, and Turó de la Rovira. Individuals from the LBA levels of Minferri (NR 6) exhibit a mean $\delta^{13}\text{C}$ value of $-19.8 \pm 1.30\text{‰}$, displaying a different diet in comparison to the cattle from Tossal de Baltarga and Sant Esteve d'Olius (Grandal-d'Anglade *et al.* 2019). Indeed, the latter two settlements display the lowest $\delta^{13}\text{C}$ values for cattle remains among the studied sites. For the EIA levels at Can Roqueta, the bone remains of eight cattle were analysed. These exhibit a mean $\delta^{13}\text{C}$ value of $-17.8 \pm 3.50\text{‰}$ and display great variability (Albizuri *et al.* 2021). This suggests that C_4 plants made an important contribution to their diet, contrary to the dietary patterns observed at the four studied sites. In the Roman period, individuals from Vila de Madrid (NR 7) and Carrer Ample 1 (NR 4) sites display a mean $\delta^{13}\text{C}$ value of $-21.0 \pm 1.10\text{‰}$ and $-21.1 \pm 1.40\text{‰}$, respectively (Rissech *et al.* 2016; Salazar-García *et al.* 2022). Concerning $\delta^{15}\text{N}$ values, there are no statistically significant differences between cattle from the four sites studied and those from the E-MBA and LBA levels of Can Roqueta (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021). On the other hand, statistically significant differences are observed when comparing the six cattle from the E-MBA of Minferri (Kruskal-Wallis tests: $H = 4.42$; $p = 0.0355$), the eight individuals from the EIA of Can Roqueta (Kruskal-Wallis tests: $H = 10.33$; $p = 0.001306$) and the Roman Period cattle from Vila de Madrid (NR 7; Kruskal-Wallis tests: $H = 4.521$; $p = 0.03348$) and Carrer Ample 1 (NR 4; Kruskal-Wallis tests: $H = 7.714$; $p = 0.005476$; Rissech *et al.* 2016; Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021; Salazar-García *et al.* 2022).

For *Sus domesticus* (NR 31), the mean $\delta^{13}\text{C}$ value is $-20.3 \pm 0.47\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $6.0 \pm 1.51\text{‰}$; pigs from Mas Castellar de Pontós display a mean value of $-19.78 \pm 0.87\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.53 \pm 1.07\text{‰}$ in $\delta^{15}\text{N}$ (NR 4); at Tossal de Baltarga the two pigs present a mean value of $-20.16 \pm 0.03\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $7.02 \pm 2.00\text{‰}$ in $\delta^{15}\text{N}$; pigs from Sant Esteve d'Olius exhibit a mean value of $-20.37 \pm 0.32\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $6.17 \pm 1.80\text{‰}$ in $\delta^{15}\text{N}$ (NR 16); pigs from Turó de la Rovira provides a mean value of $-20.45 \pm 0.39\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.71 \pm 0.99\text{‰}$ in $\delta^{15}\text{N}$ (NR 9). Pigs from the Iron Age studied sites exhibit a diet primarily based on C_3 plants. Only the individuals from Mas Castellar de Pontós present enriched $\delta^{13}\text{C}$ values (mean value of $-19.78\text{‰} \pm 0.87\text{‰}$), suggesting a potential contribution of C_4 plants to their diet. Nevertheless, there are no statistically significant differences among pigs from the four sites (Kruskal-Wallis test: $H = 5.115$; $p = 0.2749$). Individuals from Tossal de Baltarga and Sant Esteve d'Olius display a higher protein content compared to those from Mas Castellar de Pontós and Turó de la Rovira, although there are no statistically significant differences (Kruskal-Wallis tests: $H = 1.657$; $p = 0.6466$). It is possible to compare the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of these pigs with those of individuals from Minferri (E-MBA), as well as from both the E-MBA and LBA levels of Can Roqueta, from Vila de Madrid and Carrer Ample 1 (RP). In general, Minferri pigs (NR 2) predominantly consume C_3 plants (mean $\delta^{13}\text{C}$ values of $-20.2 \pm 0.20\text{‰}$) and exhibit a higher protein intake (mean $\delta^{15}\text{N}$ values of $8.6 \pm 1.30\text{‰}$) compared to the Iron Age individuals, especially those from Mas Castellar de Pontós and Turó de la Rovira (Grandal-d'Anglade *et al.* 2019). The two individuals from the LBA phase at Can Roqueta display a mean $\delta^{13}\text{C}$ value of $-18.1 \pm 1.20\text{‰}$,

suggesting a possible contribution of C_4 plants to the pigs' diet. The mean $\delta^{15}\text{N}$ value is $8.7 \pm 2.50\text{‰}$, consistent with the average value observed during the E-MBA at Minferri and higher than the mean value of Iberian pigs (Albizuri *et al.* 2021). During the EIA at Can Roqueta, the pigs (NR 6) were fed mainly on C_3 plants (mean $\delta^{13}\text{C}$ values of $-19.5 \pm 1.80\text{‰}$) and had a protein intake in line with previous chronologies, although it showed a slight decrease, with mean $\delta^{15}\text{N}$ values of $8.0 \pm 1.70\text{‰}$ (Albizuri *et al.* 2021). Pigs dating to the Roman period from Vila de Madrid (NR 6) and Carrer Ample 1 (NR 6) were fed on C_3 plants (mean $\delta^{13}\text{C}$ values of $-20.6 \pm 1.30\text{‰}$ and $-20.0 \pm 0.90\text{‰}$, respectively). Individuals from Vila de Madrid exhibit a mean $\delta^{15}\text{N}$ value of $4.7 \pm 6.00\text{‰}$, while those from Carrer Ample 1 display a mean $\delta^{15}\text{N}$ value of $5.4 \pm 5.70\text{‰}$ (Rissech *et al.* 2016; Salazar-García *et al.* 2022). These values suggest a diet with a lower protein content than that observed for E-MBA, LBA, and EIA and generally in line with the diet of Iron Age pigs.

When it comes to *Equus caballus* (NR 11), the mean $\delta^{13}\text{C}$ value is $-20.4 \pm 1.00\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $4.8 \pm 1.50\text{‰}$; the four horses from Mas Castellar de Pontós display a mean value of $-20.29 \pm 0.90\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.43 \pm 0.45\text{‰}$ in $\delta^{15}\text{N}$; Sant Esteve d'Olius provided a mean value of $-21.24 \pm 0.24\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.39 \pm 3.64\text{‰}$ in $\delta^{15}\text{N}$ for the two horses; at Turó de la Rovira the horses exhibit a mean value of $-20.07 \pm 1.19\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $4.49 \pm 1.26\text{‰}$ in $\delta^{15}\text{N}$ (NR 5). The comparison with six horses from the LBA phase of Can Roqueta and 28 from the EIA phase does not show substantial differences in feeding habits (Kruskal-Wallis tests: $H = 6.965$; $p = 0.1375$), except for a slightly increased consumption of C_4 plants in the forage (a mean $\delta^{13}\text{C}$ value of $-18.9 \pm 2.90\text{‰}$ and $-19.4 \pm 4.80\text{‰}$, for the LBA

and EIA phases respectively; Grandal-d'Anglade *et al.* 2021). Comparison with two individuals from the E-MIA/IP levels shows no differences in the horses' diet with respect to individuals from the Iron Age period. Indeed, the mean $\delta^{13}\text{C}$ value at Can Roqueta is $-20.4 \pm 0.10\text{‰}$ (Grandal-d'Anglade *et al.* 2021). Horses dated to the Roman period from the necropolis of Vila de Madrid (NR 8) show a mean $\delta^{13}\text{C}$ value of $-21.2 \pm 1.30\text{‰}$, which is in line with a diet primarily composed of C_3 plants, similar to the Iron Age period (Salazar-García *et al.* 2022). In contrast, the three individuals of the LR from Carrer Ample 1 show a slight integration of C_4 plants in the diet (mean $\delta^{13}\text{C}$ values of $-19.8 \pm 1.50\text{‰}$; Grandal-d'Anglade *et al.* 2021).

For *Canis familiaris* (NR 10), the mean $\delta^{13}\text{C}$ value is -19.0 ± 1.20 , and the mean $\delta^{15}\text{N}$ value is $7.3 \pm 1.51\text{‰}$; Mas Castellar de Pontós provided a mean value of $-18.58 \pm 1.48\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $6.80 \pm 1.11\text{‰}$ in $\delta^{15}\text{N}$ (NR 5) among the analysed dogs; the only dog from Sant Esteve d'Olius displays a $\delta^{13}\text{C}$ value of $-19.91 \pm \text{‰}$; the four dogs from Turó de la Rovira exhibit a mean value of $-19.55 \pm 0.85\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $8.47 \pm 1.27\text{‰}$ in $\delta^{15}\text{N}$. Dogs from Mas Castellar de Pontós, Sant Esteve d'Olius and Turó de la Rovira display similar mean $\delta^{13}\text{C}$ values (Kruskal-Wallis tests: $H = 1.151$; $p = 0.5624$). However, concerning the mean $\delta^{15}\text{N}$ values, individuals from Turó de la Rovira exhibit higher values (mean $\delta^{15}\text{N}$ values of $8.47 \pm 1.27\text{‰}$) than those from the other two Iron Age sites, although not statistically significant (Kruskal-Wallis tests: $H = 4.86$; $p = 0.08804$). Comparisons can be made between the Iron Age dog remains and those from different periods at Can Roqueta, including the E-MBA (NR 23; mean $\delta^{13}\text{C}$ values of $-19.2 \pm 1.50\text{‰}$, mean $\delta^{15}\text{N}$ values of $8.0 \pm 2.60\text{‰}$), LBA (NR

8; mean $\delta^{13}\text{C}$ values of $-18.8 \pm 2.30\text{‰}$, mean of $\delta^{15}\text{N}$ values of $8.1 \pm 4.40\text{‰}$), LBA/EIA (NR 2; mean of $\delta^{13}\text{C}$ values of $-17.7 \pm 1.40\text{‰}$, mean of $\delta^{15}\text{N}$ values of $9.3 \pm 0.40\text{‰}$), EIA (NR 13; mean of $\delta^{13}\text{C}$ values of $-17.9 \pm 2.80\text{‰}$, mean $\delta^{15}\text{N}$ values of $8.9 \pm 2.90\text{‰}$), as well as from the Roman necropolis of Vila de Madrid (NR 15; mean $\delta^{13}\text{C}$ values of $-18.9 \pm 1.10\text{‰}$, mean $\delta^{15}\text{N}$ values of $8.8 \pm 5.40\text{‰}$). The Kruskal-Wallis test reveals no substantial differences in $\delta^{13}\text{C}$ values (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021, Salazar-García *et al.* 2022). On the other hand, the ANOVA test indicates statistical differences in both $\delta^{13}\text{C}$ (ANOVA test: $F = 4.334$; $p = 0.0457$) and $\delta^{15}\text{N}$ values (ANOVA test: $F = 9.081$; $p = 0.005111$) between the dogs from different levels of Can Roqueta dated between LBA and EIA the ones from Mas Castellar de Pontós, Sant Esteve d'Olius, and Turó de la Rovira. Albizuri and colleagues (2021) hypothesise an intake of C_3 and C_4 cultivated plants in the diet of dogs from Can Roqueta, subject to human intervention. Consequently, it appears unlikely that the dogs from the Iberian Iron Age settlements studied here received a significant intake of vegetables. Regarding the mean of $\delta^{15}\text{N}$ values, dogs from Can Roqueta and those from Vila de Madrid appear to have had a diet richer in protein compared to dogs from Mas Castellar de Pontós and Sant Esteve d'Olius and thus more similar to the diet of individuals from Turó de la Rovira.

For *Cervus elaphus* (NR 7, all from Sant Esteve d'Olius), the mean $\delta^{13}\text{C}$ value is $-21.07 \pm 0.52\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $3.38 \pm 0.73\text{‰}$. The values recorded in the deer from Sant Esteve d'Olius can be compared with those from the Roman site of Carrer Ample 1. The $\delta^{15}\text{N}$ values do not display significant differences between the two sites, reflecting a purely herbivorous

diet (Kruskal-Wallis tests: $H = 0.1648$; $p = 0.6847$). Regarding $\delta^{13}\text{C}$ values, the consumption of C_3 plants is observed in both cases, albeit with significant differences due to the diverse environment around the two sites (Kruskal-Wallis tests: $H = 8.077$; $p = 0.004414$; Rissech *et al.* 2016).

For *Meles meles* (NR 1, from Sant Esteve d'Olius), the $\delta^{13}\text{C}$ value is -18.64‰ , and the $\delta^{15}\text{N}$ value is 7.14‰ .

For the birds (NR 15, of which 12 are *Gallus gallus*), the mean $\delta^{13}\text{C}$ value is -19.8 ± 0.92 , and the mean $\delta^{15}\text{N}$ value is $8.0 \pm 1.13\text{‰}$; chickens from Sant Esteve d'Olius exhibit a mean value of $-19.05 \pm 0.45\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $7.79 \pm 0.47\text{‰}$ in $\delta^{15}\text{N}$ (NR 5), whereas the ones from Turó de la Rovira display a mean value of $-20.20 \pm 0.45\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $8.61 \pm 1.20\text{‰}$ in $\delta^{15}\text{N}$ (NR 7). The chickens from the two Iberian Iron Age sites display $\delta^{15}\text{N}$ values compatible with a diet rich in both plant and animal proteins. This dietary pattern is also observed in chickens from the Roman sites of Vila de Madrid (NR 4; mean $\delta^{15}\text{N}$ values of $8.6 \pm 2.70\text{‰}$) and Carrer Ample 1 (NR 1; with a $\delta^{15}\text{N}$ value of 10.3‰).

Finally, for *Oryctolagus cuniculus* (NR 14), the mean $\delta^{13}\text{C}$ value is $-21.5 \pm 0.83\text{‰}$, and the mean $\delta^{15}\text{N}$ value is $5.3 \pm 2.44\text{‰}$; rabbits from Mas Castellar de Pontós present a mean value of $-21.49 \pm 0.33\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $3.89 \pm 0.77\text{‰}$ in $\delta^{15}\text{N}$ (NR 6); at Sant Esteve d'Olius rabbits display a mean value of $-21.69 \pm 1.27\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $5.93 \pm 2.97\text{‰}$ in $\delta^{15}\text{N}$ (NR 5); at Turó de la Rovira the three rabbits exhibit a mean value of $-21.27 \pm 0.88\text{‰}$ in $\delta^{13}\text{C}$ and a mean value of $7.02 \pm 2.84\text{‰}$ in $\delta^{15}\text{N}$. Both $\delta^{13}\text{C}$ (Kruskal-Wallis tests: $H = 0.7638$; $p = 0.6826$) and $\delta^{15}\text{N}$ values (Kruskal-Wallis tests: $H = 4.64$; $p = 0.09777$) of rabbits from Mas Castellar de Pontós, Sant

Esteve d'Olius, and Turó de la Rovira do not exhibit statistically significant differences. However, some variability in the $\delta^{15}\text{N}$ values is observed among the individuals from Sant Esteve d'Olius and Turó de la Rovira (mean values of $5.9 \pm 2.97\text{‰}$ and $7.0 \pm 2.84\text{‰}$, respectively). The results of the Iberian rabbits are similar to those of the two individuals from the Roman site of Vila de Madrid (Salazar-García *et al.* 2022).

3.2 Sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ results

Results of the intra-tooth sequences of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are summarised in Table 4.7 and fully presented in Figure 4.8 and Table S1 (see Annex). The $\delta^{13}\text{C}$ values from all samples range from -6.9‰ to -13.9‰ , with a mean of $-11.3 \pm 1.14\text{‰}$. The mean $\delta^{13}\text{C}$ value within each specimen varies from -10.5‰ to -13.0‰ , maximum values range from -6.9‰ to -12.3‰ , and minimum values range from -11.3‰ to -13.9‰ . The $\delta^{18}\text{O}$ values from all samples range from 2.6‰ to -4.6‰ , with a mean of $0.4 \pm 1.6\text{‰}$. The mean $\delta^{18}\text{O}$ value within each specimen varies from 1.6‰ to -2.9‰ , maximum values range from 2.6‰ to -1‰ , and minimum values range from 1.0‰ to -4.6‰ .

The sheep from Mas Castellar de Pontós display a sinusoidal pattern and clear maximum and minimum events in both the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences, reflecting the seasonal cycle. The second molar of individual MC 20102 is the only exception, with a narrow amplitude of the oxygen sequence. On the other hand, the carbon sequence appears consistent with the others. The $\delta^{18}\text{O}$ sequences from Tossal de Baltarga exhibit high intra-tooth variation along the crown, with a sinusoidal pattern and clear maximum and minimum events. Individual BTB 3270 presents an incomplete oxygen sequence, resulting in an incomplete seasonal

Table 4.7 Summarised oxygen ($\delta^{18}\text{O}_{\text{V-PDB}\text{‰}}$) and carbon ($\delta^{13}\text{C}_{\text{V-PDB}\text{‰}}$) values measured on bioapatite samples from the lower second (M_2) and third (M_3) sheep molars: mean, range, maximum (max), and minimum (min) isotopic values.

Teeth	Sample	n	$\delta^{18}\text{O}_{\text{V-PDB}\text{‰}}$				$\delta^{13}\text{C}_{\text{V-PDB}\text{‰}}$			
			Mean	Range	Max.	Min.	Mean	Range	Max.	Min.
M ₂	MC 11144	16	0.2	2.8	1.8	-1.0	-11.8	-5.5	-8.2	-13.7
	MC 12023	19	-0.6	3.9	1.6	-2.3	-11.8	-3.8	-9.8	-13.6
	MC 20102	14	1.6	1.1	2.1	1.0	-10.8	-5.0	-7.5	-12.4
	MC 20160	13	0.0	4.1	2.2	-1.9	-10.9	-7.0	-6.9	-13.9
	MC 20165	14	1.0	3.2	2.6	-0.6	-11.9	-1.8	-11.0	-12.7
M ₃	MC 11132	14	0.0	2.3	1.0	-1.2	-11.9	-2.1	-10.8	-12.9
	MC 11134	13	-0.1	2.8	1.2	-1.5	-11.1	-3.2	-9.2	-12.3
	MC 11138	17	0.2	2.7	1.4	-1.3	-10.9	-3.1	-9.5	-12.6
	MC 20160	15	-0.6	2.9	0.5	-2.4	-11.7	-2.8	-10.6	-13.4
	MC 20165	15	-0.3	2.6	0.9	-1.6	-11.3	-3.2	-9.1	-12.3
M2	BTB 3249	16	-1.8	6.0	1.4	-4.6	-11.2	-1.6	-10.5	-12.1
	BTB 3270	10	-0.6	3.9	0.9	-3.0	-11.3	-2.5	-9.4	-12.0
	BTB 3271	13	-2.2	5.1	0.6	-4.5	-12.1	-1.0	-11.5	-12.5
M3	BTB 3031	16	-1.3	4.6	1.1	-3.5	-11.2	-1.3	-10.6	-11.8
	BTB 3270	12	-2.0	7.0	3.4	-3.6	-10.9	-1.8	-9.8	-11.6
M2	O 174	18	-1.1	4.2	1.0	-3.2	-11.8	-1.2	-11.1	-12.3
	O 205	15	-2.9	3.3	-0.8	-4.1	-11.9	-0.8	-11.5	-12.3
	O 318	13	-1.0	3.4	0.3	-3.0	-10.9	-0.8	-10.5	-11.3
	O 348	15	-2.0	2.9	-1.0	-3.9	-11.7	-1.9	-10.9	-12.8
	O 478	16	-0.8	3.9	0.9	-3.0	-10.7	-2.1	-9.7	-11.8
	O 482	16	-1.3	4.0	0.8	-3.2	-13.0	-1.0	-12.3	-13.3
	O 484	14	-2.3	2.9	-0.7	-3.6	-11.5	-1.7	-10.9	-12.6
M3	O 205	19	0.2	4.0	2.5	-1.6	-11.2	-1.6	-10.3	-12.0
	O 318	20	-0.6	4.3	1.9	-2.4	-10.8	-1.2	-10.2	-11.4
	O 478	14	0.0	5.2	2.1	-3.1	-10.6	-1.8	-9.8	-11.6
M2	TR 725	18	0.6	2.2	1.9	-0.4	-10.5	-2.8	-8.9	-11.7
	TR 763	17	0.9	2.6	2.2	-0.4	-11.6	-3.0	-9.7	-12.7
	TR 831	17	0.9	2.3	2.4	0.1	-11.0	-5.6	-7.6	-13.2
M3	TR 725	16	0.8	2.0	1.9	-0.1	-10.5	-4.2	-8.3	-12.5
	TR 763	15	1.3	2.5	2.6	0.1	-11.7	-3.0	-10.3	-13.2
	TR 831	13	0.6	2.4	1.4	-1.0	-10.5	-3.5	-9.1	-12.5

cycle, due to wear. In contrast, the $\delta^{13}\text{C}$ sequences of all individuals show low intra-tooth variation. All sheep from Sant Esteve d'Olius display oxygen sequences with great variation along the dental crowns, characterised by a sinusoidal pattern. On the other hand, the carbon sequences display a narrower variation amplitude. At Turó de la Rovira, the sheep $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences exhibit intra-tooth variations and follow a sinusoidal pattern, with clear maximum and minimum peaks. Due to the young age and consequent incomplete mineralisation of the crown, it is not possible to identify maximum and minimum events in

the third molar of individual TR 831. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences included in this study have been previously interpreted in two publications investigating the reproduction and mobility strategies adopted by Iberian Iron Age communities (Messana *et al.* 2023a, 2023b).

Although the majority of the individuals analysed display $\delta^{13}\text{C}$ values indicative of a diet primarily composed of C_3 plants, some sheep (MC M2 11144, MC M2 20102, MC M2 20160, and TR M2 831) exhibit evidence of a seasonal contribution of C_4 plants to their diet. These specimens

display $\delta^{13}\text{C}$ values up to -7.7‰ when the oscillating curves of isotopic values reach their maximum peaks along the tooth enamel crown. This suggests a contribution of C_4 plant not throughout the whole year but during specific and brief periods of life. As previously reported (see section 1.2), the threshold above which $\delta^{13}\text{C}$ values indicate the intake of C_4 plants is -23‰ . To account for the fossil fuel effect, a correction of $+1.5\text{‰}$ is necessary, resulting in a value of -21.5‰ for pre-industrial plants and -7.4‰ in the enamel of large ruminant mammals feeding on them.

4. Discussion

4.1 Livestock feeding habits

The feeding habits of the sheep at the four studied sites appear to be generally homogeneous. The mean and range values of both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ show no significant differences. This indicates that this species' requirements and maintenance must have been similar across the four settlements. Overall, when comparing the results obtained from sheep with those of the other species present in the four Iberian settlements, it is observed that the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values exhibited by sheep fall within an intermediate position relative to those of the other *taxa* at all sites (Figure 4.7). To better understand the feeding habits of the sheep, these are compared below with those of the herbivorous and omnivorous species analysed as a local baseline.

In general, sheep exhibit a more carbon-enriched and varied diet, with a higher protein contribution compared to goats (Figure 4.9a). The only exception is the data from Tossal de Baltarga. Unfortunately, only one goat from this site was analysed, which displays a diet enriched in carbon and nitrogen compared to sheep (Figure 4.7). While

both species consume C_3 plants, sheep tend to be grazers whereas goats are likely browsers and consume higher vegetation (Papachristou 1997; Bartolomé *et al.* 1998; Sanon *et al.* 2007; Dwyer 2009; Jiménez-Manchón *et al.* 2023). The difference in carbon values between the two species could be attributed to their distinct feeding behaviours.

Sheep and cattle both display similar variability in their $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, which is consistent with the grazing nature of both species (Figure 4.9a). However, at Mas Castellar de Pontós the cattle show a different dietary pattern compared to sheep, with higher carbon values suggesting the incorporation of C_4 plants in their diet (Figure 4.7). At Tossal de Baltarga, the sheep diet appears to be enriched in carbon and less varied in protein compared to the cattle. In Sant Esteve d'Olius and Turó de la Rovira, on the other hand, the sheep diet is on average more enriched in both carbon and nitrogen.

Comparing the results of collagen analyses between sheep and pigs from the four settlements, no significant differences are observed in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values and their variability. However, pigs tend to exhibit less variability in $\delta^{13}\text{C}$ values than sheep (Figure 4.9a). At Mas Castellar de Pontós, sheep and pigs display a similar diet, although sheep exhibit slightly lower $\delta^{13}\text{C}$ values on average (Figure 4.7). A different picture emerges at Tossal de Baltarga. Here one of the two pigs, an adult, has a diet considerably enriched in animal protein (Figure 4.7). However, drawing general conclusions on feeding patterns based on data from only two individuals is risky. At Sant Esteve d'Olius, both species show similar $\delta^{13}\text{C}$ values, although sheep display greater variability. Furthermore, pigs have a higher protein intake in their diet

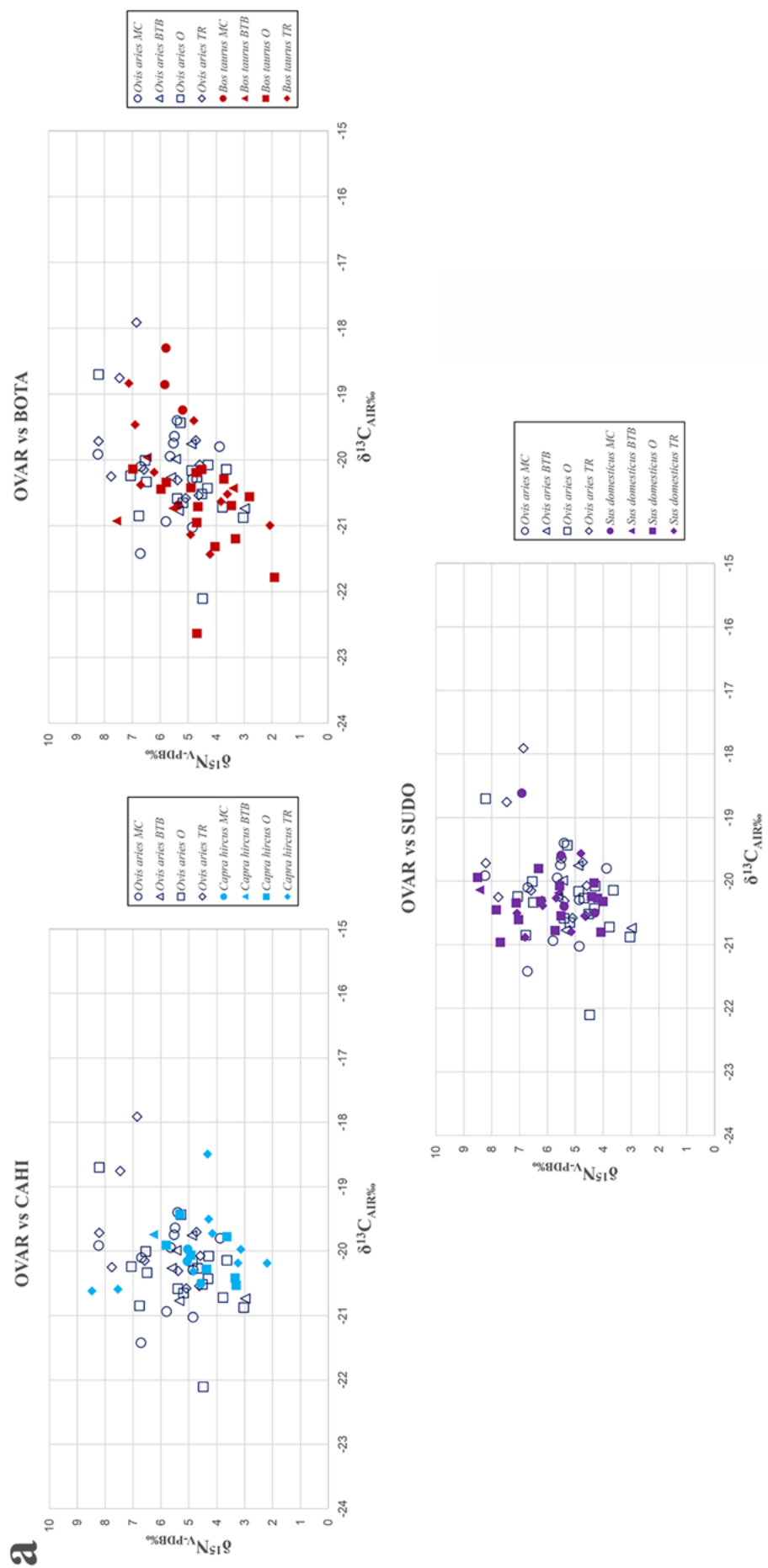
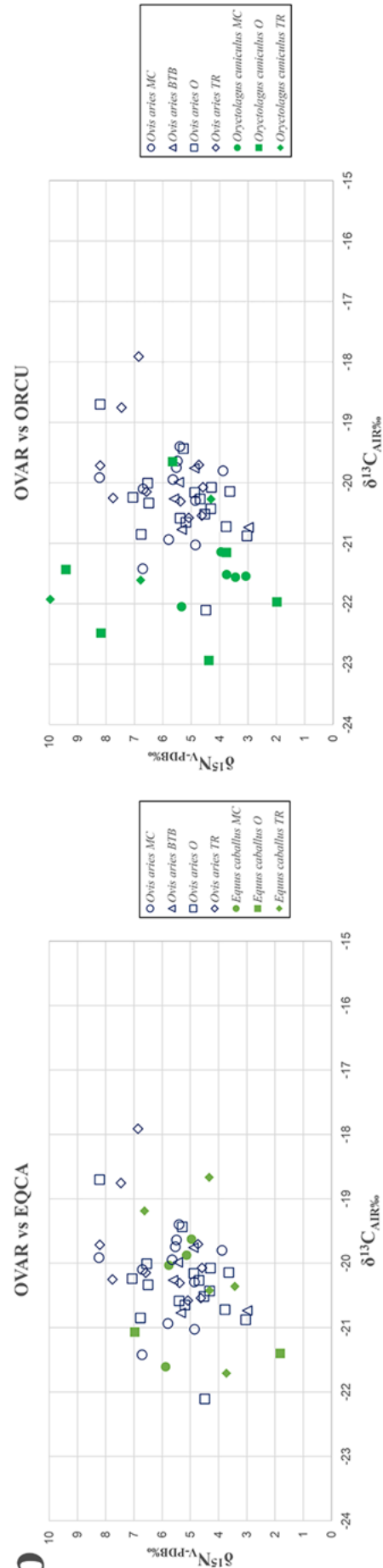
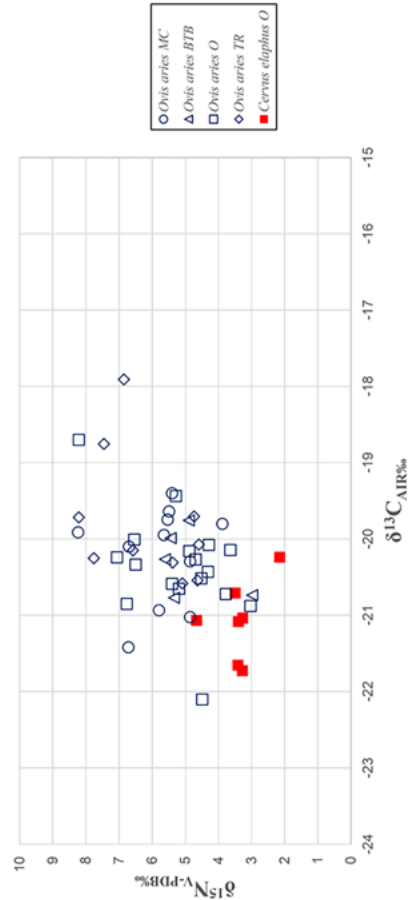


Figure 4.9 Carbon ($\delta^{13}C_{AIR\text{‰}}$) and nitrogen ($\delta^{15}N_{V-PDB\text{‰}}$) values of bone collagen samples from the four Iberian Iron Age sites. Comparison between sheep and goats, sheep and cattle, and sheep and pigs (**Figure 4.9a**); comparison between sheep and horses, sheep and rabbit, and sheep and deer (**Figure 4.9b**).

b



OVAR vs CEEL



(Figure 4.7). Turó de la Rovira sheep exhibit a significantly carbon-enriched and more varied diet compared to pigs and with a higher protein consumption (Figure 4.7).

Horses from three of the four Iron Age settlements (Mas Castellar de Pontós, Sant Esteve d'Olius, Turó de la Rovira) exhibit a vegetal diet similar to that of sheep, as both are grazing species. However, the horses' diet is less enriched in protein compared to sheep (Figure 4.9b). It was not possible to analyse the calcined remains of the only horse (BTB EQCA 3224) from Tossal de Baltarga. The sheep feeding in Mas Castellar de Pontós appears to be more enriched and varied in protein compared to horses. It is possible that the horses also received a supplement of C_4 cereals in their forage, as indicated by the wide variability and higher $\delta^{13}C$ values (Figure 4.7). The limited number of horses remains analysed at Sant Esteve d'Olius (NR 2) prevents us from drawing general conclusions about the feeding management of this species in the *Lacetan* settlement. Nonetheless, the two individuals show a purely C_3 plant-based diet, with lower $\delta^{13}C$ values than the sheep. Overall, the sheep's diet appears more enriched in protein, although the two horses display completely different nitrogen values (Figure 4.7). At Turó de la Rovira, sheep exhibit less variability in their vegetal diet and a higher protein intake compared to the horses (Figure 4.7).

Sheep and rabbits exhibit significantly different vegetal diets. Rabbits from the three Iberian sites (no remains are available for Tossal de Baltarga) have much lower $\delta^{13}C$ values than sheep, indicating the consumption of plants and resources from dense forest habitats. Although the protein content of the diet is similar for both animals, the $\delta^{15}N$ values of rabbits show greater variability within sampled sites (Figure

4.9b). At Mas Castellar de Pontós, sheep display a diet enriched in both carbon and nitrogen (Figure 4.7). At Sant Esteve d'Olius and Turó de la Rovira, the sheep's diet is confirmed to be rich in carbon, whereas rabbits exhibit higher protein intake and greater variability in nitrogen content (Figure 4.7).

When comparing the feeding habits of the sheep from the four Iron Age sites with those of the deer from Sant Esteve d'Olius, it is evident that sheep display a more variable diet enriched in both carbon and nitrogen (Figure 4.9b). The same trend is observed within the *Lacetan* settlement, confirming the distinct diets of the two species and probably suggesting differences between wild and domestic grazer herbivores (Figure 4.7).

The feeding habits of sheep have been previously analysed through the $\delta^{13}C$ values resulting from bulk collagen analyses. They are now further interpreted by considering the $\delta^{13}C$ values obtained from the sequential analysis carried out on dental bioapatite. The sequential analysis confirms that the sheep primarily consumed C_3 plants. However, it reveals seasonal variability in the carbon values of the four settlements, in contrast to the general homogeneity observed in the sheep's diet through collagen analysis (Figure 4.8). Indeed, along the dental crown, the $\delta^{13}C$ values indicating consumption of C_4 plants by individuals coincide with the duration of the maximum $\delta^{18}O$ values recorded during the warm season. As a result, based on the variability and amplitude of the carbon sequences, the four sites can be differentiated into two groups, with individuals from Mas Castellar de Pontós and Turó de la Rovira exhibiting wider ranges compared to individuals from Tossal de Baltarga and Sant Esteve d'Olius. The carbon sequences of the first group (MC and

TR) are generally wide and closely mirror the fluctuations of the oxygen sequences, which are indicative of seasonal changes. These variations result from a feeding regime influenced by seasonal climatic variability and the resulting availability of plant resources throughout the year. In this context, plants experience water stress during warmer periods, leading to higher $\delta^{13}\text{C}$ values, which coincide with higher $\delta^{18}\text{O}$ values. In the second group (BTB and O), the $\delta^{13}\text{C}$ sequences generally display a very narrow amplitude, while the oxygen sequences exhibit seasonal variations. This suggests that feeding in these settlements was not strongly subject to seasonally-based plant consumption. Therefore, it is plausible that the sheep's diet was supplemented with additional fodder and water during periods when pasture resources were limited.

At Mas Castellar de Pontós, the eight individuals analysed generally had a diet primarily based on C_3 plants. However, three individuals - MC 11144, MC 20102, and MC 20160 - show a different pattern. We know that individual MC 11144 was born in spring, whilst individuals MC 20102 and MC 20160 were born in autumn (Messana *et al.* 2023a). The analysis of the $\delta^{13}\text{C}$ sequence obtained from the M_2 of individual MC 11144 suggests that C_4 plants contributed to its diet during its second summer alive (Figure 4.8). However, since there is no information available about the individual's first summer alive due to the crown wear, it is unclear whether this supplement of C_4 plants was a systematic and repetitive seasonal practice or a punctual or sporadic event. In both individuals MC 20102 and MC 20160, there is evidence of a contribution of C_4 plants in their diet during their first summer (Figure 4.8). For individual MC 20160, it was also possible to analyse its M_3 and

the $\delta^{13}\text{C}$ sequence displays a reduced amplitude and values consistent with a C_3 plant-based diet. Therefore, our data show that C_4 plants were integrated into the diet of individual MC 20160 on a punctual basis rather than seasonally. It appears that at Mas Castellar de Pontós the feeding strategies for sheep included the occasional contribution of C_4 plants, likely cereals, to the fodder when grazing resources were limited (i.e. summer peak). Tracing this dietary supplement is more challenging when considering the values obtained from bulk collagen analyses carried out on bone remains. For instance, the $\delta^{13}\text{C}$ value obtained from the mandible of individual 20160 is -19.91‰, which provided an attenuated signal of the C_4 plants' contribution to the diet in its later years (Table 4.5). Similar values around -19‰ are observed in the bone collagen of five other individuals, suggesting that they might have consumed C_4 forage at some point in their lives, but seasonal contribution could be masked in multi-year values.

In the *Ceretan* settlement of Tossal de Baltarga, the carbon sequences of three of the four sheep individuals analysed - BTB 3031, BTB 3249, and BTB 3271 - exhibit a very narrow amplitude, indicating minimal to no variations in the diet on a seasonal basis. Regarding individual BTB 3270, after its second summer, a simultaneous increase in carbon values and a decrease in oxygen values is observed. This results in an inverse relationship between the two sequences. The increase in carbon values corresponds to the consumption of carbon-enriched plants in a drier environment, suggesting a change in pastures due to an altitudinal movement to lowlands areas. After the second winter, carbon values decrease as oxygen values increase, indicating another change in altitude and feeding habits, and a return to the original

location (Messana *et al.* 2023b). In this case, the increase in $\delta^{13}\text{C}$ values is not due to the contribution of C_4 plants in the forage. The sequential analyses on the dental bioapatite are consistent with the results obtained from the bulk collagen analyses, confirming a purely C_3 diet for the sheep.

At Sant Esteve d'Olius, the $\delta^{13}\text{C}$ values from the seven sheep individuals analysed depict a herd primarily fed on C_3 plants, with no significant seasonal variations in diet. Even individual O 205, which moved from a different location to Olius during its third winter, displays a similar pattern of the $\delta^{13}\text{C}$ sequence, with a limited amplitude in its early years (Messana *et al.* 2023b). The sequential analysis results are consistent with those obtained from the bulk collagen analysis, except for individual O 484. For the latter, the collagen analysis indicates a contribution of C_4 plants to its diet, which is not reflected in the sequential analysis. This suggests that the dietary integration in individual O 484 must have occurred after the mineralisation of its second lower molar.

Finally, two out of the three sheep individuals from Turó de la Rovira - TR 725 and TR 763 - both born in spring, exhibit wide and seasonally fluctuating $\delta^{13}\text{C}$ sequences. On the other hand, the third individual - TR 831 - born at the beginning of summer, practised short-range seasonal mobility along a low altitudinal gradient (Messana *et al.* 2023a, b). Indeed, after its first winter, an increase in oxygen values coincides with a decrease in carbon values, indicating a movement towards a wetter environment and a corresponding change in diet. After the second summer, another change in the pasture occurs, which is reflected in a decrease in oxygen values and a simultaneous increase in carbon values

(Messana *et al.* 2023b). Therefore, the change in feeding is due to a seasonal change in pastures. Specifically, individual TR 831 fed on wetter pastures during its second summer, before returning to Turó de la Rovira and feeding there during its second winter. An additional noteworthy aspect is the recording of high $\delta^{13}\text{C}$ values towards the end of individual TR 831's first summer, suggesting a potential contribution of C_4 plants to its diet, although data is not conclusive at all. Previous isotopic studies on reproduction strategies and livestock mobility at Turó de la Rovira suggest that there was a differentiated flock management and, probably, a division of the herd into two distinct groups. The data presented in this study reinforce this idea, further articulating the livestock management strategies adopted in the *Laietan* settlement. Part of the flock, specifically those born in the spring, would have remained in Turó de la Rovira year-round. On the other hand, the individuals born during summer, starting from their second year of life, would have joined the practice of seasonal altitudinal mobility. Among this latter group, the newborn individuals, that were too young to undergo seasonal migration, would have stayed in the settlement and received a supplement of C_4 plants into their fodder. This management, including the migration of only a part of the flock and dietary supplements, might have been influenced by the limited availability of pastures during the dry summer season. However, the limited number of individuals analysed hinders in-depth deductions. The collagen analysis performed on the remains of ten sheep suggests a diet mainly consisting of C_3 plants. Nevertheless, the $\delta^{13}\text{C}$ value obtained from the mandible of individual TR 831 (-18.76‰) could indicate the integration of C_4 plants in its diet. An

even higher value (-17.91‰) is observed in individual TR 819, suggesting the consumption of C_4 plants during its lifetime. Unfortunately, neither M_2 nor M_3 were recovered from this individual, making it impossible to verify if it underwent a similar management as individual TR 831.

4.2 Livestock feeding management

The data obtained from the collagen isotope analysis shed new light on the diversified livestock feeding strategies adopted by Iberian communities during the Middle/Late Iron Age. Particular focus was reserved for sheep and caprines in general, which were the most prevalent species in the four settlements.

The homogeneous feeding pattern observed for sheep in the four studied settlements reveals the particular care given to the management of this species. According to Columella in Book VII of *De re rustica*, the Greek philosopher Celsus affirmed that sheep are a very delicate species, confirming the special attention reserved for them by shepherds (VII.II.2). In addition, the Roman author advises feeding them in abundant grassy pastures, while Varro recommends year-round outdoor grazing for the flock (Colum. VII.III.9; Varro II.II.7). Both authors agree on the importance of keeping sheep away from shrubs and bushes to prevent damage to their fleece. With the currently available data, it seems that the feeding habits of sheep appear to be similar not only among the Iberian communities but also over time, as suggested by the analysis carried out in the Roman necropolis of Vila de Madrid (Salazar-García *et al.* 2022).

It is plausible that sheep and goats shared pastures within the same flock. However, the two species differ in their dietary preferences. Goats primarily consume C_3 plants in all four settlements

and display a less diversified, lower in carbon and nitrogen diet compared to sheep. Columella and Varro point out that goats are more inclined to pasture in rugged areas and wooded glades, consuming shrubs and brambles (Colum. VII.VI.1; Varro II.III.6-7). In addition, Varro highlights the behavioural differences between the two caprine species, with sheep exhibiting a docile and gregarious nature, whereas goats are inclined to disperse and move around in impervious environments (Varro II.II.3). Therefore, it is conceivable to imagine a mixed herd in which both species, although pasturing in proximity, have access to distinct plant resources. Finally, the exploitation of different products from both species should also be considered. While sheep were primarily exploited for wool, goats were mainly exploited for milk and its derived products such as cheese. The different feeding strategies employed by herders may correspond to diverse livestock practices and exploitation. The generally lower nitrogen values observed in goats compared to sheep in all four sampled sites could suggest a legume supplement in their diet. Indeed, legumes provide excellent hay and their nutrient and plant protein content can have positive effects on milk production and composition (Morand-Fehr and Sauvant 1980; Harris *et al.* 1996; Ahmed and Nour 1997; Bonanno *et al.* 2013).

The results of the sequential analysis of second and third molars from sheep paint an even more intricate picture of their seasonal feeding management. Although limited to approximately the first two years of an individual's life, this analysis offers a highly accurate yearly and seasonal resolution. The north-eastern Iberian Peninsula is characterised by the Mediterranean climate, known for its high variability

and marked seasonal fluctuations in pasture availability and rainfall (Davies, 1941; Ruiz and Ruiz 1986; Oteros-Rozas *et al.* 2013). Therefore, it becomes crucial to detect, at a seasonal scale, the livestock feeding strategies adopted by Iron Age Iberian shepherds to adapt to the Mediterranean basin's fluctuating climatic conditions. Additionally, the integration of crop residues into the livestock diet likely adhered to a seasonal pattern tied to their availability. The possible use of these animals for field clearance between sowing seasons cannot be excluded. Finally, seasonal variations in feeding habits could be related to forage supplementation for pregnant females or males preparing for mating. In *De re rustica*, Book II, Varro states that rams should be fed more fodder and barley two months before mating to strengthen them (II.II.13). Therefore, it cannot be ruled out that cereal integration in an individual's diet might also depend on these factors.

The results obtained from the analysis of cattle remains reveal a general similarity in diet with sheep. However, when considering the data obtained from each site, the diet of the two species differs. Furthermore, the cattle diet varies between the different settlements. Therefore, Iron Age Iberian herders employed diverse feeding strategies for cattle between settlements. Moreover, within the same settlement, they fed caprines and cattle with different types of fresh vegetation and/or fodder. Indeed, the dietary requirements of each animal may differ according to species, age, sex, and intended use. Therefore, the differences observed in the diets of caprines and cattle within the same settlement, as well as among cattle from different settlements, are not unexpected. However, this livestock management approach implies the employment

of specialised and tailored feeding strategies for each species reared in the settlement, along with the availability of diverse pastures and forage resources to suit the specific needs of each animal. The introduction of C₄ plants in the cattle diet at Mas Castellar de Pontós suggests a supplement of cultivated cereals in their forage. The integration of C₄ plants into the livestock diet in the rural settlement is well attested by the results obtained through sequential isotope analysis on sheep teeth. Moreover, the presence of both winter and spring crops within the settlement would have guaranteed the availability of crop residues for a significant portion of the year, particularly during seasonal periods when grazing resources were limited (Canal 2000; Canal 2002). Columella mentions the use of cereal chaff for cattle feed, emphasising millet as the most prevalent option, followed by barley and wheat (VI.III.3). The extensive presence of millet, a C₄ cereal, within the rural establishment, supports the plausibility of its utilisation for feeding the cattle of Mas Castellar de Pontós (Canal 2000; Canal 2002). However, Columella and Varro recommend grazing cattle in grassy, well-watered pastures (Colum. VI.III.2; Varro II.V.14). Moreover, in drier areas, Columella suggests feeding them with legumes and hay meadows within the stables (VI.III.3). At Tossal de Baltarga, both cattle and sheep were primarily fed on C₃ plants. However, the cattle's vegetal diet appears more homogeneous compared to those of sheep. This may depend on the frequentation of different pastures for the two animals: cattle grazed in open pastures, whereas sheep pastured in the wooded areas surrounding the settlement, consuming a more heterogeneous variety of plants. The cattle from Sant Esteve d'Olius had a diet very similar to that of sheep.

However, some individuals exhibit values suggestive of having consumed plants from closed-canopy forests. According to Varro in Book II of *De re rustica*, cattle graze in wooded areas and consume undergrowth and foliage (II.V.11). Therefore, a non-generalised contribution of these plants to their diet within the *Lacetan* settlement cannot be ruled out. At Turó de la Rovira, the cattle feeding habits were similar to those of sheep. Nevertheless, their diet manifested a higher degree of variability. Some individuals consumed small add-ons of plants from wooded areas, while others included C₄ plants in their diet. It is feasible that the cattle were allowed to graze unrestricted around the *Laietan* settlement, feeding on both cultivated and uncultivated terrains. With all these data, we can propose that the feeding strategies adopted by Iron Age Iberian herders for cattle varied from one settlement to another according to the requirements of each community. In contrast, the few collagen results available for the Bronze Age and Early Iron Age settlements in the north-east of the Iberian Peninsula revealed a more homogeneous scenario, with the integration of C₄ plants into the cattle's diet (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021). On the other hand, the cattle feeding habits during the Roman period indicate a diet primarily based on C₃ plants (Rissech *et al.* 2016; Salazar-García *et al.* 2022). The data obtained from the four Iron Age sites are thus in an intermediate position between the earlier and later periods, demonstrating the great adaptability and variability of Iberian communities in livestock management.

In the four Iron Age settlements, the pigs' alimentation primarily consisted of C₃ plants, which aligns with the dietary patterns of sheep. Additionally, their intake of animal protein was limited,

suggesting a mildly omnivorous diet. A slightly higher consumption of animal protein is observed in pigs from Sant Esteve d'Olius. However, the nitrogen values suggest that the diet was still predominantly herbivorous, probably with minimal contribution from culinary waste. It is possible that pigs were allowed to graze freely or semi-freely in the outdoors, rather than reared in enclosures with a controlled diet. Both Columella and Varro mention the use of legumes as pig fodder (Colum. VII.IX.9; Varro II.IV.6). Their inclusion in suids' diet could have contributed to the generally low nitrogen values observed, as possible signs of omnivorous behaviour might have been attenuated by legume consumption. A previous study by Lösch and colleagues (2006) provided support for this hypothesis suggesting the consumption of legumes by sheep, goats, and pigs from the Pre-Pottery Neolithic B site of Nevalı Çori to explain the lower $\delta^{15}\text{N}$ values recorded in these *taxa*. On the other hand, the available data on Bronze and Early Iron Age Iberian pigs indicates a feeding strategy rich in animal protein (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021). In contrast, the few data available from the Roman Period suggest that pig dietary habits experienced a significant shift, resulting in a generally lower but more varied animal protein content (Rissech *et al.* 2016; Salazar-García *et al.* 2022). Therefore, as in the case of cattle, the data from Iron Age Iberian settlements related to pigs' feeding strategies falls into an intermediate position between earlier and later periods.

This study documents the seasonal consumption of C₄ plants by sheep at Mas Castellar de Pontós. This feeding habit is also observed in cattle and probably horses, but it is not possible to determine whether the consumption

was continuous or sporadic for these two species. The results of both bone collagen and sequential dental analyses suggest a supplement of C_4 plants also in the diet of cattle from Turó de la Rovira. Therefore, it is evident that Iron Age Iberian shepherds supplemented livestock's diet with C_4 cereals according to their necessity.

The integration of C_4 plants into sheep diet was not common during prehistoric and protohistoric times in the north-east or the entire Iberian Peninsula (Navarrete *et al.* 2019; Navarrete *et al.* 2023; Navarrete *et al.* 2024; Tejedor-Rodríguez *et al.* 2021; Martín *et al.* 2021; Sierra *et al.* 2021). Nevertheless, it is important to consider the geographic position of the Iberian Peninsula, which is located in the southernmost area of Europe. This may have provided opportunities for C_4 plants to thrive in drier ecological niches. Regarding protohistoric times in the north-eastern Iberian Peninsula, Albizuri and colleagues (2021) suggest that dogs from the Can Roqueta site, dated between the Late Bronze Age and the Early Iron Age (1300 and 550 cal. BC), consumed C_4 cereals (millet), following the human diet. Furthermore, the data obtained from foxes also indicate consumption of C_4 cereals, suggesting a commensal relationship on the part of foxes during the Bronze Age. Finally, cattle also display values compatible with the integration of C_4 plants into their diet. Therefore, it cannot be ruled out that herbivorous species occasionally or seasonally consumed these plants. Further research could expand our understanding of the consumption of C_4 plants by sheep and other livestock, providing a more comprehensive view.

5. Conclusion

The data from this study reveal for the first time the livestock feeding strategies adopted by Middle/Late Iron Age communities in the north-eastern Iberian Peninsula. The bulk collagen analysis on the bone remains of the main *taxa* from four Catalan sites and the sequential analysis in the second and third lower molars of sheep have unveiled the complex, diversified, and adaptive nature of the husbandry practices employed by Iron Age Iberian populations. Sheep, the predominant species during the Iron Age, were provided with specific care and a homogeneous diet, mainly consisting of C_3 plants at all four sites. However, their feeding habits were subject to seasonal changes depending on pasture availability and settlement requirements. As a result, different patterns of sheep diet management were observed in the four settlements studied. At Mas Castellar de Pontós and Turó de la Rovira, the seasonal climatic variability and the rarefaction of pastures during the summer influenced the feeding habits of the herds. Additionally, during the summer months, the sheep's diet at both settlements was supplemented with C_4 plants. Herd feeding strategies at Tossal de Baltarga and Sant Esteve d'Olius appeared less reliant on seasonal variations in pasture availability. There probably was human intervention in sheep feeding, with the contribution of C_3 fodder and water when pasture resources were limited, especially during winter.

The data obtained from the other main domestic species in the four settlements (goats, cattle, and pigs) have expanded and enhanced the knowledge of livestock husbandry practices employed by the Iron Age Iberian communities. Furthermore, the integration of results from bulk

collagen and sequential analyses performed on sheep remains allowed a more comprehensive understanding of the carbon composition of collagen from other domestic *taxa*. The results reveal a complex husbandry system in which, within the same settlement, each species was subject to individualised feeding strategies. We suggest that these varied not only depending on the needs of each animal but also in response to the availability of pasture and fodder, as well as the demands for secondary products specific to each community. This livestock feeding management required advanced knowledge of animal requirements, a great ability to adapt to the local environment, and a considerable workforce.

Therefore, this livestock system likely relied on a considerable workforce dedicated to the care and management of the livestock. This degree of labour organisation suggests that animal husbandry played a more crucial role in the economy of the Iron Age Iberian communities than it has been given so far. Hence, it is plausible that there was a division and specialisation of activities within the settlements, with agriculture on one side and animal husbandry on the other. Nevertheless, these two systems were interlinked and perfectly integrated into their respective schedules.

The results obtained on livestock feeding strategies are consistent with those related to reproduction strategies and mobility of sheep presented in Messina *et al.* (2023a) and Messina *et al.* (2023b). Indeed, the different husbandry practices employed by the Iberian communities are also reflected in the distinct patterns of both sheep reproduction and mobility in the four settlements.

On a methodological level, this study

provides a more comprehensive insight into the feeding strategies of sheep through the combination of isotopic analyses on the organic fraction of bone remains (bulk collagen) and the mineral fraction of dental remains (sequential analysis on enamel bioapatite). The sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ allowed the reconstruction of sheep's dietary habits during approximately their first two years of life, with a seasonal resolution. This level of detail is inevitably forfeited through $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis on bulk collagen. Nevertheless, this analysis revealed the protein sources, whether of plant or animal origin, consumed by the main species, sheep including, in the four Iron Age Iberian settlements during approximately their final decade of life. Therefore, both analyses proved to be complementary and necessary for a complete understanding of the livestock feeding strategies adopted by Iberian shepherds and the reasons guiding their adoption.

This research highlights the adaptive nature of the Iron Age Iberian populations and their ability to manage their livestock in a way that maximises their resources while meeting each animal's specific needs. Furthermore, the carbon and nitrogen values from cattle and pigs respectively occupy an intermediate position between those available in the literature for the Bronze Age to Early Iron Age and the Roman period. Thus, based on the currently available data, there does not appear to have been an abrupt change in the feeding strategies of these two species between the Iron Age and the Roman period. Finally, the results presented in this study constitute the first data on livestock feeding strategies for the Middle/Late Iron Age in the north-eastern Iberian Peninsula. The massive number of remains and the variety of species analysed provide the first baseline for interpreting $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

results for this chronology and area. The results obtained demonstrate that it is imperative to conduct further research on additional Iron Age Catalan settlements, as well as Roman sites, to investigate the evolution of livestock feeding strategies during the transition between these two periods. Furthermore, the crucial relevance and considerable potential of isotopic analyses for a broader understanding of the economic and social dynamics within protohistoric societies is evident.

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Author Contributions

C.M. selected, sampled, and prepared the bone and dental remains for isotope analysis, wrote the main manuscript, prepared figures, processed and interpreted the data. C.T. and L.C. contributed to the data interpretation and reviewed the manuscript. All the authors approved the submitted version.

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Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files).

Code availability

Not applicable.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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UNIVERSITAT ROVIRA I VIRGILI

TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC) : A MULTI-ISOTOPE RESEARCH

Chiara Messina



Discussion

5

5.1 Methodological contributions

The results of this thesis have provided novel and fundamental data for the understanding of husbandry practices in the north-east of the Iberian Peninsula during the Middle and Late Iron Age. However, the contribution of this thesis goes beyond its historical relevance. The multi-isotope approach employed has also yielded valuable contributions on a methodological level for each of the three topics addressed. The following subparagraphs outline, point-by-point, the three methodological aspects covered in this study.

5.1.1 Data from M_2 and M_3 in the study of the duration and distribution of seasonal sheep births

The sequential analysis of $\delta^{18}\text{O}$ values to infer seasonal sheep reproduction patterns was performed on both the second and third lower molars of the archaeological specimens. Among these, it was possible to model the sequences of both M_2 and M_3 for seven individuals, allowing a direct

comparison of the data obtained from their modelling. The results from all M_2 s and M_3 s analysed coincide in indicating that sheep births occurred throughout the year at the studied sites (see Section 4.1.2, Figure 3). Furthermore, M_2 and M_3 pairs consistently record the individual's birth within the same seasonal group, either natural (winter/early spring) or 'out-of-season' (late summer/autumn). As for the two unmodelled M_3 s (MC 20160 and TR 831), the oscillation of their sequences, according to the reference by Balasse *et al.* (2023), suggests that they belong to the summer/autumn birth group, in agreement with their respective M_2 s. However, the precise data obtained from the M_3 s reveal some divergences from their respective M_2 s. These discrepancies suggest that the timing of crown formation in M_3 s and their inter-individual variability between sampled specimens may affect the final interpretations of the data. Specifically, the results of the M_3 s modelling exhibit a lower seasonal resolution, leading to a higher x_0/X ratio than the birth interval resulting from the respective M_2 s and a narrower birth period. Thus, all modelled pairs display an average

difference of 0.17 (2.02 months) between the M_2 (x_0/X) and M_3 (x_0/X_{real}) results.

Blaise and Balasse (2011) and Tornero and colleagues (2013) previously observed the impact of M_3 characteristics on the accurate seasonality (Blaise and Balasse, 2011) and birth season (Tornero *et al.*, 2013) determination in modern and archaeological sheep, respectively. However, studies by Knockaert (2017) and Balasse *et al.* (2023) suggest that inter-individual variability in M_3 is unlikely to result in the incorrect attribution of winter/spring births to autumn and vice versa.

In this PhD dissertation, the study presented in the second article (see Section 4.1.2), data from M_2 and M_3 were combined. For the first time, it was possible to interpret the results relying on a solid basis, following the recent modern reference set by Balasse *et al.* (2023). The results obtained from this test bench have confirmed that inter-individual variability in the timing of third molar growth does not result in misattribution of the birth group, despite different levels of inaccuracy. Moreover, this study demonstrates that M_3 s from the four Iberian Iron Age sites display a slightly higher level of imprecision (2.02 months) compared to the values reported in the literature for both modern references and archaeological specimens. Indeed, the inter-individual variability in the M_3 development timing of modern Lacune sheep is approximately 1.5 months, whereas the modelled and normalised M_2 and M_3 data from early 5th millennium BC individuals from Cheia (Romania) is 1.8 months (Tornero *et al.*, 2013; Knockaert, 2017; Balasse *et al.*, 2023).

The morphology of M_3 s and their generally lower wear stage compared to M_2 s make them accessible for selection

and subsequent sampling. However, it must always be borne in mind the inaccuracy of data from M_3 s at the seasonal level. Therefore, whenever possible, it is recommended to rely on data obtained from both M_2 and M_3 or to prioritise the analysis of M_2 s when determining sheep reproductive patterns. For our study, we focused exclusively on the data obtained from M_2 s to infer and discuss the timing, duration, and distribution of seasonal herd births. This decision was made due to the methodological constraint of the data obtained from the M_3 s and the sufficient data obtained from the M_2 s. This does not undermine the validity of the data obtained from the M_3 s and the methodological contribution made by their study.

5.1.2 Combining sequential $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopes with $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios

The third paper in this thesis (see Section 4.2.1) presents the first study to trace the seasonal altitudinal mobility of sheep flocks in the north-eastern Iberian Peninsula during protohistoric periods through the relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. Previous research has employed other proxies, both biogeochemical and morphometric, to identify possible sheep movements (Valenzuela *et al.*, 2016, 2018; Colominas *et al.*, 2019b). The results of these studies provided no evidence of long-distance seasonal mobility, suggesting that Iron Age Iberian communities practised limited-scale husbandry.

The sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values was integrated with the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements in the same dental series to explore in more detail the movements along different altitudinal and geological areas. The main objective was to determine the

allochthonous origins of sheep and to detect evidence for mobility, rather than identifying the accurate origins. At the same time, it was possible to test the compatibility and effectiveness of the combination of these proxies. This integrated approach, combining sequential analyses of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values and the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio, makes it possible to compensate for the potential limitations of using only one method. It also allows for a wider range of data, increasing the resolution of the results and their interpretations.

Relying on the results of strontium analyses makes it possible to clarify the causes of the increase in $\delta^{13}\text{C}$ values in an individual during winter. This increase may be caused either by a change in pasture due to an altitudinal movement, or by a shift in the diet involving the consumption of C_4 plants. The presence of C_4 cereals such as millet (*Panicum milliaceum*) and foxtail millet (*Setaria italica*) is attested in almost all the settlements studied in this thesis (Canal, 2000, 2002; Riera *et al.*, 2020; Colominas *et al.*, 2023). Their eventual use as livestock fodder during winter would overshadow the signals of seasonal mobility displayed by the inverse relationship between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences. On the other hand, relying exclusively on strontium analysis, it is not possible to identify altitudinal movement between areas with the same lithological composition or geologically complex and patchy. Furthermore, the interpretation of the results remains strictly dependent on the bioavailable strontium maps. The combination of different isotopic proxies overcomes all these limitations.

This study confirmed that correspondence and complementarity exist between the results obtained through the inverse relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ and those derived from the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Indeed,

in individuals in which the parallel sequences of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ indicate sedentary behaviour, the $^{87}\text{Sr}/^{86}\text{Sr}$ values do not exhibit significant differences. Similarly, in individuals displaying an inverse relationship between the two sequences, the $^{87}\text{Sr}/^{86}\text{Sr}$ values vary significantly between them, confirming movement between different geological areas. Furthermore, the results demonstrate the effectiveness of integrating data obtained from the two proxies and the huge potential of multi-isotope analyses to effectively trace evidence of livestock movements across different altitudinal and geological areas.

5.1.3 Integration of bulk $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ collagen analysis and sequential enamel $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis

The final article composing this thesis (see Section 4.3.1) investigates sheep feeding habits through multi-stable isotope analyses: bulk $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis of bone collagen and sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis of dental enamel. The decision to rely on both analyses rests on the determination to gain the most comprehensive insight possible into the feeding strategies adopted by Iberian herders during the Middle/Late Iron Age.

The results obtained from the isotope analysis on bone collagen are essential for understanding the long-term dietary behaviour of sheep. In addition, they reveal the protein sources, plant or animal, consumed by each individual and provide information on the trophic level (Ambrose and Norr, 1993; Tykot, 2004). However, they do not allow seasonal resolution in the reconstruction of sheep feeding habits. The stage of this study, the north-eastern Iberian Peninsula, is characterised by the Mediterranean

climate, known for its high variability and marked seasonal fluctuations in pasture availability and rainfall (Davies, 1941; Oteros-Rozas *et al.*, 2013; Ruiz and Ruiz, 1986). It is therefore crucial to determine, on a seasonal scale, the livestock feeding strategies adopted by Iron Age Iberian shepherds to adapt to the fluctuating climatic conditions of the Mediterranean basin. Furthermore, the eventual integration of crop residues into the livestock diet likely followed a seasonal pattern depending on their availability.

The high-crowned teeth (hypsodonts) of sheep allowed the bulk isotope analysis of bone collagen to be complemented by the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequential analysis. This type of analysis enabled the reconstruction of the livestock's feeding habits with a seasonal resolution, limited to the first two years of life. This level of detail would inevitably have been forfeited by performing $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses on bulk collagen alone. Consequently, it would have been more challenging to trace the seasonal contribution of C_4 in the diet of the individuals analysed. Indeed, seasonal dietary intakes may be masked in multi-annual values. The combination of the two proxies for the study of sheep feeding habits also allowed further interpretation of the $\delta^{13}\text{C}$ values at the C_3 - C_4 limit, obtained from the analysis of bone collagen from other species. Thus, the two analyses proved to be complementary and necessary for a complete understanding of the livestock feeding strategies adopted by Iron Age Iberian shepherds and the reasons that guided their adoption.

This approach has been successfully applied in other chronological and geographical contexts and with different hypsodont species (Balasse *et al.*, 1999; Palmqvist *et al.*, 2003; Gillis, 2012; Gillis *et al.*, 2013; Dai *et al.*, 2016;

Vaiglova *et al.*, 2018; Blanz *et al.*, 2020; Kamjan *et al.*, 2020; Makarewicz, 2023; Trentacoste *et al.*, 2023). Regarding the protohistoric chronologies of the north-eastern Iberian Peninsula, previous isotopic studies on livestock feeding habits have always been limited to multi-annual resolution, analysing the bone remains of sheep and other main domestic and wild species (Grandal-d'Anglade *et al.*, 2019; Grandal-d'Anglade *et al.*, 2021; Albizuri *et al.*, 2021). This research is therefore the first to rely on the combination of isotopic analyses on the organic fraction of bone remains (bulk collagen) and the mineral fraction of dental remains (sequential analysis on enamel bioapatite) for this chronotopic context.

5.2 Reproduction patterns and demographic management

This paragraph discusses the results obtained on the first of the three key aspects of livestock management: the control of sheep reproduction. The data obtained from the four Iron Age Iberian settlements represent the first evidence of livestock reproduction strategies in the north-eastern Iberian Peninsula for this chronology. Identifying the management of lambing and births of sheep is one of the key parameters to understanding the socioeconomic strategies of Iberian pastoral communities and their organisation. Indeed, the birth season and the duration of the lambing period impact labour organisation, seasonal availability of animal products, and mobility patterns (Balasse *et al.*, 2017; Hadjikoumis *et al.*, 2018; Walsh *et al.*, 2023).

The results presented in the first two articles of this thesis (see Section 4.1) suggest that sheep births occurred throughout the year in the north-east of

the peninsula during the Middle/Late Iron Age, albeit there were substantial differences in herd management among settlements (see Section 4.1.2, Figure 4). Here, reproduction strategies were closely linked to social organisation, economic needs, environmental conditions, pasture and fodder availability.

The sequential oxygen isotope analyses performed on sheep molars provided valuable insight into their season of birth, the duration of the lambing period, and the anthropogenic manipulation carried out by Iron Age Iberian herders. The results revealed a wide range of livestock management practices and shepherds' interventions.

Among the settlements studied in this thesis, Mas Castellar de Pontós stands out as the most socially and economically complex, and the one for which the most information is available. Similarly, its herding system also appears articulated, featuring a bi-modulated reproduction model. Lambing occurred during two different seasons: from late winter to spring, corresponding to natural births in temperate climates, and in autumn (Hafez, 1952; Jewell and Grubb, 1974; Santiago-Moreno *et al.*, 2000; Gootwine, 2011; Gómez-Brunet *et al.*, 2012). The shepherds of the *Indigeta* settlement not only extended the birth season, resulting in two distinct groups of sheep giving birth at different times of the year but also interfered with the duration of the lambing period. Indeed, autumn births were synchronised within a narrow period, as a strategic choice of the herders. In this way, the labour force and efforts required to monitor lambing and take care of newborns were restricted to a specific time-limited period (Balasse *et al.*, 2020).

This high level of human intervention in the reproductive traits of sheep required extensive knowledge of their physiology, availability of facilities and resources, and specialised labour. Firstly, it was necessary to control female-male interactions during predetermined times. For instance, autumn births require the separating of rams and ewes in the autumn and their reunion in the spring (Tornero *et al.*, 2020; Balasse *et al.*, 2023). The environmental conditions surrounding the rural establishment were also favourable. The Empordà plain is marshy and rich in ponds and wetlands. The anthracological analyses also indicate an ecosystem of riparian vegetation and wooded areas around the settlement (Ros and Piqué, 2002). During the Iron Age-Roman period, the north-western Mediterranean experienced warmer and/or moister conditions and strong seasonality, with frequent precipitation in the cold season (González-Sampériz *et al.*, 2017). Thus, the favourable and non-extreme climatic and environmental conditions at Mas Castellar de Pontós allowed farmers to provide sufficient fodder to support autumn and winter lamb lactation. Cereal integration into the herd's diet could compensate for any shortage of pasture and fodder. The settlement's complex agricultural system, which includes both winter and spring crops, would have provided crop residues for a large portion of the year. In support of this hypothesis, the results of sequential carbon isotope analyses indicated a seasonal integration of C₄ plants, probably millet, into the sheep's diet during the summer season (see Sections 4.3.1 and 5.4).

The 'out-of-season' and prolonged lambing period extended the availability of animal products, especially fresh milk, throughout the year. Therefore,

the herders of Mas Castellar de Pontós likely managed sheep reproduction to exploit secondary products intensively (Gómez-Brunet *et al.*, 2012; Tornero *et al.*, 2020). The sheep mortality profiles in the rural establishment, with a predominance of adult and older individuals (from 48 to over 96 months) and mostly females, also suggest the exploitation of the flock to obtain secondary products, i.e. milk and wool (Colominas, 2008; Colominas, 2013a). Controlling livestock reproduction is crucial for managing and maintaining herd size. Therefore, one possible reason for having two different birth seasons in the same settlement could be the increase in herd size. The constant presence of a significant number of sheep would have allowed for varied flock management, including the sacrifice, exploitation, or exchange as a commercial product of part of the individuals. Previous zooarchaeological analyses have demonstrated the presence of a large flock (approximately 60-80 individuals) within the rural settlement (Colominas, 2013a). It seems plausible that the pastoral and agricultural calendars were well integrated and interconnected within the rural settlement. It cannot be ruled out that there was a clear division and specialisation of labour, which would have allowed for the employment of complex strategies and the maximum exploitation of crop fields and livestock.

De-seasonalisation was not a systematic practice during the Iron Age. Each community managed the herd's reproduction according to its own needs and adapted to the environmental conditions of the territory. Therefore, at Tossal de Baltarga, the herders relied on the natural birth season of the sheep, from late winter to spring. On the other hand, the duration of the lambing

season for the analysed individuals suggests anthropogenic manipulation, as their births appear to be grouped in a short time frame. In this way, the care labour for the pregnant ewes and lambs was minimised, ensuring their survival. Scheduling autumn births or extending the lambing season would not have been profitable for the shepherds of the Ceretan settlement. Births in autumn would have exposed the newborns to the harsh winter temperatures in the high mountains and the decrease in pastures due to snow cover. Births between late winter and spring would have also facilitated the incorporation of some of the sheep into the practice of seasonal altitudinal mobility to the lowlands after summer, during overwintering (See Sections 4.2.1 and 5.3).

The settlements of Sant Esteve d'Olius and Turó de la Rovira have revealed a third, distinct reproduction pattern for sheep. Although the births are restricted to a single group, the lambing period is prolonged due to anthropogenic scheduling. At Sant Esteve d'Olius, births occurred from winter to early summer, with a significantly extended lambing period compared to the natural breeding season. Similarly, at Turó de la Rovira, the birth period from spring to summer was more prolonged than the natural one. The herders of these two settlements may have had various reasons for interfering with the duration of the sheep lambing season. Zooarchaeological data from both sites indicate that sheep were exploited for meat and, secondarily, wool and milk (Colominas 2013b, 2019a). Hence, it is reasonable to assume that shepherds from both settlements would be interested in the availability of secondary products for an extended period, although not year-round. It cannot be excluded that summer births could be an intermediate step towards

a de-seasonalisation of the herd in the autumn or the result of 'catch-up mating' due to low spring fertility. Regarding Turó de la Rovira, seasonal sheep mobility may have influenced birth scheduling (see Section 4.2.1 and 5.3). It is noteworthy that the only individual born during the summer is also the only one to undertake seasonal mobility to wetter areas during its second summer. However, due to the limited number of individuals analysed, detailed deductions in this respect are precluded.

5.3 Sheep mobility

This section discusses the results concerning the second key aspect of this thesis: the livestock mobility strategies employed by Iron Age Iberian populations. The adoption of a model of herd mobility must be sustainable, profitable, and motivated by specific environmental and/or economic reasons. This type of pastoralism implies specialisation in livestock breeding and an in-depth knowledge of the surrounding environment and available natural resources. Moreover, it requires prior communication and organisation with the populations involved to ensure the unrestricted movement of flocks and the possibility of commercial opportunities. Finally, practising herd mobility entails the ability to manage any disruptions that may occur during the displacement, such as diseases and injuries (Brun, 1996; Euba, 2008; Otero-Rozas *et al.*, 2012).

Once again, the data obtained from the four Iron Age settlements testify to the use of various husbandry strategies by the Iberian communities. Mas Castellar de Pontós records a sedentary pattern of herd management. The Tossal de Baltarga community, on the other hand, practised seasonal altitudinal mobility

between two different ecosystems. At least one individual from Sant Esteve d'Olius engaged in unidirectional mobility. Finally, at Turó de la Rovira, short-range seasonal mobility along a low altitudinal gradient is evidenced.

Of all the sites studied in this thesis, only Mas Castellar de Pontós showed no evidence of short- or long-range mobility among the analysed sheep. As previously reported (see Section 5.2), the *Indigeta* settlement was characterised by an extremely articulated and well-interconnected agricultural-pastoral system, which was suitable for a sedentary herding system. The bi-modulated reproduction pattern, along with year-round crop residues and favourable environmental and climatic conditions, allowed the herd to remain in the settlement throughout the year. Thus, there were no environmental or economic factors that induced livestock mobility. The strontium values observed in Individual 20160 are not significantly different from each other (0.71447, 0.71454, 0.71471; see Section 4.2.1, Figure 5). However, unexpectedly they do not align with the local geology as indicated by the geological map of the Alt Empordà (Institut Cartogràfic i Geològic de Catalunya, 2023). The absence of a bioavailable strontium baseline for this area limits the interpretation of these data, preventing the prediction of the biosphere strontium signal around the settlement. To further interpret the data and clarify the range of expected strontium values, it is necessary to establish a first baseline of bioavailable strontium in the Mas Castellar de Pontós area.

In the Cerdanya region, the herders of Tossal de Baltarga faced unique challenges that demanded tailored strategies to cope with the harsh Pyrenean winter. Indeed, during the cold season, pastures were significantly

reduced due to the snow cover. As previously reported in sections 4.1.2 and 5.2, a primary adaptation to the environmental constraints was the manipulation and reduction of the sheep births in late winter/mid-spring. Moreover, the data on sheep feeding habits indicate an anthropogenic intervention in their seasonal diet. Indeed, the sheep's feeding strategies involved supplementing fodder and water during periods of limited pasture resources (see Sections 4.3.1 and 5.4). Finally, the *Ceretan* shepherds adopted a third strategy to address Pyrenean environmental constraints, which entailed the seasonal altitudinal movement of a portion of the herd to lowland pastures during overwintering. By doing so, they increased the availability of pastures for the livestock. Thus, Individual 3270 joined the practice of vertical mobility by descending to lowland locations after its second summer and during its second year of life. After its second winter, it underwent another change in altitude, returning to the Cerdanya. This movement, along with the consequent change of pasture during the first two years of life, is confirmed by the three $^{87}\text{Sr}/^{86}\text{Sr}$ values. Indeed, these vary substantially from each other along the M_2 and M_3 of Individual 3270 (0.70967, 0.71026, 0.71194; see Section 4.2.1, Figure 5). Moreover, the strontium value recorded during its first summer spent in the settlement area aligns with the expected range for the surrounding area of Tossal de Baltarga. However, the remaining two values diverge from the expected local range. The second value corresponds to the isotopic signal recorded during the individual's second winter spent in the lowlands. The third value, covering the third summer, likely reflects the signal recorded during the return journey to Cerdanya.

It cannot be ruled out that the other two individuals from the same building (G), Individual 3249 and Individual 3271, also engaged in seasonal altitudinal movement. Their young age and the absence of their respective M_3 s preclude a definitive interpretation. However, the resemblance of their $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences with those of Individual 3270 and the limited period of births at the site suggest that the three individuals might have experienced similar environmental conditions and mobility patterns. Finally, Individual 3031, coming from a different building, displays a sedentary pattern in its M_3 . Unfortunately, its M_2 is missing.

Considering the limited number of individuals recovered from the Iberian phase of the settlement, the available data suggest great flexibility in husbandry practices at Tossal de Baltarga. Indeed, only a portion of the herd spent the winter at lower altitudes. The reasons behind this selective mobility could have been multiple. Firstly, it must be clarified whether this practice resulted from the independent movement of individual family groups to the lowlands or whether it was a strategy planned by the entire Tossal de Baltarga community. The first hypothesis would not have been profitable, as a long-distance seasonal mobility system implies significant effort in terms of organisation and facilities and is not usually undertaken for a small flock. The second hypothesis appears more feasible. Indeed, the presence of several buildings with specialised production areas in the settlement, along with the recovery of luxury objects and a horse, suggest the existence of an elite class at Tossal de Baltarga (Morera, 2017; Olesi *et al.*, 2018; Tàrraga, 2020). The latter could have been responsible for managing the herd. It cannot be excluded that multiple small flocks from different

settlements in the Ceretan area were combined into a single large herd moving towards the lowlands. This scenario would suggest cooperation among various *Ceretan* communities, which coordinated their herding activities to optimise resources and maximise efficiency.

The seasonal altitudinal movement of individuals from building G could be part of a complementary, diversified strategy in which part of the flock remained in the settlement area, while the other part moved to the lowlands. During winter, the limited availability of vegetation would have made it impossible to provide enough pasture for the entire herd, resulting in the displacement of only a portion of it. Additionally, the decision to maintain part of the flock at Tossal de Baltarga could have been motivated by domestic consumption of sheep products. Furthermore, it cannot be ruled out that this altitudinal movement was not exclusively related to seasonal complementarity between pastures, but may also have been part of a commercial exchange relationship with lowland populations.

Between the end of the Bronze Age and the Early Iron Age, there was an increase in husbandry and agriculture in the high mountain areas of the Pyrenees. This phenomenon is evidenced by a decrease in vegetation cover in these areas (Euba, 2008; Morera, 2017; Olesti and Mercadal, 2017). It has been suggested that the seasonal vertical movements undertaken by the herds occurred between the Cerdanya plain, frequented during winter, and the high mountain areas, exploited in summer (Euba, 2008; Knockaert, 2017; Morera, 2017; Olesti and Mercadal, 2017). In the study conducted by Knockaert *et al.* (2018), $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences from two Middle and Late Bronze Age sites were analysed: Llo, located in the

Cerdanya highland area (1630 m a.s.l.), and Portal-Vielh, located on the east coast of present-day France (0 m a.s.l.). The data obtained from the isotopic analyses revealed a sedentary pattern for the coastal herd and a variety of sequences for the high-mountain individuals, including two sequences with an inverse relationship.

The authors interpret this great diversity of profiles as the adoption of various husbandry strategies to adapt to a mountain environment characterised by significant inter-annual climatic variations. One of these strategies could be seasonal altitudinal mobility. However, none of the individuals analysed in the study exhibit profiles similar to those measured in the modern references from lowland areas used by the authors as baselines. Therefore, any seasonal movements of the herd towards lower altitudes should be excluded, confirming the exploitation of medium and high mountain areas and a full adaptation to the mountain environment during this period.

From the 5th century BC, the *Ceretans* centralised their settlements in the middle and lower Cerdanya and focused on agricultural production (Olesti and Mercadal 2017). Moreover, Cerdanya witnessed a new territorial pattern, with *oppidum*-type settlements (Morera 2017; Olesti and Mercadal 2017). In this context, the one observed at Tossal de Baltarga is the first evidence of vertical descendant mobility from the Pyrenees to the lowlands. Considering the preceding discussion, the data from Tossal de Baltarga pave the way for the image of a more integrated and connected Ibero-Pyrenean world with its contemporary lowland communities than previously attested.

The isotope analyses of sheep from Sant Esteve d'Olius would confirm

the relationship between the two areas. Indeed, the results revealed the presence of at least two individuals in the settlement with external provenance to Solsonès. Individuals 205 and 348 exhibit low oxygen values in their M_2 , suggesting they come from high-altitude areas. Therefore, their movement is unidirectional towards the *Lacetan* settlement rather than seasonal. The sequential analyses of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ and the $^{87}\text{Sr}/^{86}\text{Sr}$ analysis performed on the M_3 of Individual 205 support this interpretation. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences switch from parallel in the M_2 to inverse in the M_3 . Moreover, the $^{87}\text{Sr}/^{86}\text{Sr}$ value recorded in the M_2 (0.71019; see Section 4.2.1, Figure 5) differs significantly from those recorded in the corresponding M_3 (0.70914, 0.70914) and in the M_2 s of Individuals 174 and 484 (0.70947, 0.70928 and 0.70955, 0.70947, 0.70937, respectively). Furthermore, the highly homogenous lithology of the Solsonès region confirms that the strontium value recorded in Individual 205's M_2 is anomalous. As a result, the latter migrated and reached Olius during its third winter.

Sheep from high-altitude areas, probably the Pyrenees, may have been brought to the settlement for commercial purposes involving product exchanges. This would have allowed the *Lacetan* herders to diversify and/or renew their flocks by engaging in exchanges with populations from higher mountain regions. Solsonès is widely recognised for its production and trade of rock salt, which is indispensable not only for preserving meat and cheese but also for the sustenance of livestock (Olesti and Mercadal, 2017). Indeed, sheep require salt as an essential nutrient, and the preference for rock salt over sea salt often stems from its higher sodium chloride content and purity (Titler and Curry, 2011; Luna

Loayza, 2013; Manrique, 2017; Marcos Pinto, 2019). Moreover, it can be easily conveyed in block form (Weller, 2004; Olesti and Mercadal, 2017). The earliest evidence of rock salt extraction in the *Muntanya de Sal* of Cardona, the only salt mountain in Western Europe, situated slightly beyond 20 km from Sant Esteve d'Olius, dates back to the Middle Neolithic (Weller, 2002; Weller and Fíguls, 2007; Fíguls *et al.*, 2013). Polished stone tools from the Vall Salina at Cardona were likely used for mining activities, based on the technological analysis (Weller, 2002; Weller and Fíguls, 2007; Fíguls *et al.*, 2013). Salt was monopolised by the state during Roman times and was subject to specific taxation measures (Olesti and Mercadal, 2017; Olesti, 2022). Furthermore, historical evidence attests to the presence of a control point within the Cardona production area dating back to the 2nd-1st centuries BC (Olesti and Mercadal, 2017). The rock salt extracted from Cardona was conveyed to Gaul and Italy through a route that passed through Solsonès, Alt Urgell, and Cerdanya before reaching contemporary French territory (Obiols *et al.*, 2009). Likewise, livestock destined for the summer pastures of the Pyrenees would have followed the same path (Obiols *et al.*, 2009; Olesti, 2022). During the medieval period, the so-called *strata Kardonensis*, recognised as a pivotal route for the supply of rock salt, established a connection between Solsonès and the Eastern Pyrenees (Olesti and Mercadal, 2017; Olesti, 2020). In modern documents, this thoroughfare is referred to as *camí Cardoner* or *camí saliner de Cardona* and remained in use until the first half of the 20th century (Obiols *et al.*, 2009; Guardia and Obiols, 2014). Consequently, the Solsonès-Cerdanya axis has been well-documented over the centuries.

The unidirectional movement recorded at Sant Esteve d'Olius and the seasonal mobility detected at Tossal de Baltarga, attest to contacts between the lowland and high-altitude areas. The exact location of the origin or destination of the two movements cannot be determined. Nevertheless, it should not be dismissed the hypothesis that the movements recorded in the two settlements are interconnected as part of a commercial relationship between the mountainous *Ceretan* region and the rich pre-Pyrenean Iberian area. The resources of the high mountain (wood, summer pastures, livestock) were likely of interest to pre-Pyrenean centres. Similarly, the resources of the Solsonès (salt, wintering pastures, Mediterranean imports) would have been appealing to *Ceretan* communities (Olesti and Mercadal, 2007). The complementary use of pastures and the exchange of products between different communities requires collaboration agreements or pacts between different political entities. The results of this doctoral dissertation document this type of connection linked to livestock for the first time in the northern Iberian world (Olesti *et al.*, 2023).

At Turó de la Rovira, a different pattern of herd movement is observed. Here, a portion of the flock engaged in short-distance seasonal mobility along a low altitudinal gradient. Of the three individuals analysed, two display sedentary behaviour, while the remaining sheep (Individual 831), exhibits a mobility pattern. Specifically, after winter, Individual 831 migrated and spent its second summer in wetter areas. The $\delta^{18}\text{O}$ values recorded in the molars of this individual are not compatible with a high-altitude environment (Knockaert *et al.*, 2018). Therefore, Individual 831 engaged in a seasonal short-range movement. Afterwards, it returned to

the *Layetan* settlement, where it spent its second winter. The $^{87}\text{Sr}/^{86}\text{Sr}$ values recorded in two of the individuals (725 and 831) confirm this pattern. The values obtained from the molars of the sedentary Individual 725 are extremely similar to each other and consistent with the expected values surrounding the settlement (0.71008, 0.71016; see Section 4.2.1, Figure 5). The $^{87}\text{Sr}/^{86}\text{Sr}$ value from the M_3 of Individual 831, recorded in winter, is accordant with the previous ones (0.71016). This confirms that the individual returned to Turó de la Rovira during its second winter. In contrast, the two $^{87}\text{Sr}/^{86}\text{Sr}$ values recorded during the second summer diverge from the previous ones and are lower than the expected range (0.70967, 0.70965; see Section 4.2.1, Figure 5).

The Mediterranean basin experiences summer dryness, which leads to limited fodder resources (Jalut *et al.*, 2009; Reiser and Kutiel, 2009; Turco *et al.*, 2017). It is therefore not surprising the evidence of seasonal mobility to wetter pastures at Turó de la Rovira, located a few kilometres from the coast. However, only part of the herd underwent a seasonal migration. Despite the potential challenges posed by limited water and food resources during the summer, the sedentary portion of the herd managed to survive in the settlement. Indeed, the $\delta^{13}\text{C}$ values of the two sedentary individuals (725 and 763) exhibit wide and seasonal fluctuating sequences, mirroring those of $\delta^{18}\text{O}$. Thus, their diet was affected by seasonal climatic variability, as a consequence of which the plants experienced water stress during warmer periods (see Sections 4.3.1 and 5.4).

The herders from Turó de la Rovira may have practised a differentiated flock management strategy, dividing the herd into two distinct groups. Thus,

part of the herd would remain within the settlement year-round, while the other group would practise seasonal mobility. This division of the herd may have been intended to alleviate the farmers' labour load during the intense summer months of agricultural activity (Cleary, 1986). This hypothesis finds reinforcement in the carpological data, which reveal a predominant cultivation of wheat and barley, along with the presence of millet and, in minor proportions, legumes, grapes, and figs (Riera *et al.*, 2020). Moreover, it should be borne in mind that short-range livestock movement generally involves small flocks (Brun 1996). Additionally, the scarcity of pastures during the dry summer season may have dictated the migration of part of the flock. Finally, as suggested in the case of Tossal de Baltarga, the domestic consumption of sheep products could have determined the retention of part of the herd in the *Layetán* settlement.

Based on the available data, it is not possible to determine with certainty the destination for the seasonal movement undertaken by the Turó de la Rovira flock. Nevertheless, it should be proposed that the flock's destination was the nearby coastal massif of the Garraf (Baix Llobregat, Barcelona). The recovery of several pastoral enclosures dated to the Iberian period (6th to 1st century BC) testifies to the passage and sheltering of livestock in this area (Cebrià *et al.*, 2003; Ejarque and Orengo, 2009). Additionally, anthracological data spanning the Late Bronze Age to Early Iron Age period indicate that anthropogenic pressure resulted in a reduction of vegetation on the massif (Ros, 1992; Riera *et al.*, 2007). The aforementioned study conducted by Valenzuela *et al.* (2018) establishes a first baseline of bioavailable strontium for the area around the Iberian site of Turó de la Font de la Canya (Avinyonet

del Penedés, Barcelona), located on a small coastal promontory between the Penedés plain and the Garraf massif. The $^{87}\text{Sr}/^{86}\text{Sr}$ values recorded by individual TR 831 during the second summer away from Turó de la Rovira deviate from the expected local ones and could be compatible with a movement towards the Vallès-Penedès depression and the Garraf massif.

5.4 Livestock feeding habits

This section discusses the main results regarding the last of the three essential elements of any husbandry system addressed in this doctoral dissertation: livestock feeding strategies. Shepherds have a direct role in managing the eating habits of their livestock and can intervene in their seasonal diet to varying degrees. The traditional management of sheep feeding habits, and livestock in general, is directly related to the surrounding environmental characteristics and the economic and subsistence needs of each community. Furthermore, livestock feeding strategies are closely linked to the previous key aspects addressed, reproduction and mobility. Traditional livestock feeding management often follows a seasonal pattern, which may involve mobility or forage integration. Thus, there may be a relationship between the agricultural calendar and forage feeding.

The data obtained from the analysis of sheep collagen from the four Catalan Iron Age sites are generally homogeneous. The mean and range of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values show no significant differences. Likely, the requirements of this species and the care and maintenance provided by the herders within the four settlements must have been similar. The sheep's diet primarily consisted of C_3 plants, with a limited consumption of vegetable protein (see

Section 4.3.1, Figure 4.7). According to the limited data currently available, it seems that the feeding habits of sheep were similar not only among Iron Age communities but also over time, as suggested by the analysis carried out in the Roman necropolis of Vila de Madrid (Barcelona) (Salazar-García *et al.*, 2022).

The data from the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sequential analyses on sheep molars allow a seasonal resolution on the feeding habits of this species. It is, therefore, possible to understand more in-depth the feeding strategies employed by the herders in each of the four settlements studied. The sequential analyses support a mainly C_3 plant diet for the sheep. However, the feeding strategies differ seasonally across the four sites. The results reveal seasonal variability in the carbon values of individuals from the four settlements, in contrast to the general homogeneity of the sheep diet observed by collagen analysis (see Section 4.3.1, Figure 4.8). Furthermore, a seasonal integration of C_4 plants is detected in some of the individuals. Indeed, along the dentary crown, the $\delta^{13}\text{C}$ values indicating the consumption of C_4 plants by individuals coincide with the duration of the maximum $\delta^{18}\text{O}$ values recorded during the warm season.

Based on the variability and amplitude of the carbon sequences, the four sites can be divided into two groups: sheep from Mas Castellar de Pontós and Turó de la Rovira with wider ranges, and individuals from Tossal de Baltarga and Sant Esteve d'Olius with narrower ones. The $\delta^{13}\text{C}$ sequences of the first group (MC and TR) are generally wide and closely mirror the sinusoidal fluctuations of the $\delta^{18}\text{O}$ sequences, indicating changes occurring in consumed diet plants following natural dynamics. Thus, the feeding regime was influenced

by seasonal climatic variability and the consequent availability of plant resources during the year. During warmer periods, indicated by higher $\delta^{18}\text{O}$ values, plants experience water stress, resulting in higher $\delta^{13}\text{C}$ values than during the winter period. In the second group (BTB and O), the $\delta^{13}\text{C}$ sequences generally exhibit a very narrow amplitude, whereas the $\delta^{18}\text{O}$ sequences display seasonal variations. This suggests that the feeding in these settlements was not strongly dependent on the seasonal consumption of plants. Therefore, it is plausible that during periods of limited pasture resources, the sheep's diet was supplemented with additional fodder and water.

According to data obtained from bone collagen analyses, at Mas Castellar de Pontós the herd had a diet primarily based on C_3 plants. The sequential analyses of dental enamel generally confirmed this feeding habit. However, three individuals - MC 11144, MC 20102, and MC 20160 - show a different pattern. The analysis of the $\delta^{13}\text{C}$ sequence obtained from the M_2 of Individual MC 11144 suggests the consumption of C_4 plants during its second summer of life (see Section 4.3.1, Figure 4.8). Due to crown wear, it was not possible to obtain any information on the individual's first summer of life. Consequently, it is unclear whether this integration of C_4 plants was a systematic and repeated seasonal practice or a one-off event. Individuals MC 20102 and MC 20160 display evidence of a contribution of C_4 plants in their diet during their first summer (see Section 4.3.1, Figure 4.8). Individual MC 20160's M_3 was also analysed and the $\delta^{13}\text{C}$ sequence exhibits a reduced amplitude and values consistent with a C_3 plant-based diet. Therefore, C_4 plants were integrated into the diet of individual MC 20160 on a punctual rather than seasonal basis.

The sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses suggest that sheep feeding strategies at Mas Castellar de Pontós included the occasional contribution of C_4 plants, probably cereals, to the fodder during the summer peak, when grazing resources were limited. Additionally, it cannot be ruled out that these animals may be used for field clearance between sowing seasons. Finally, seasonal variations in feeding habits might be related to forage supplementation for pregnant females or males preparing for mating. In Book II of *De re rustica*, the Roman author Varro recommends that rams receive increased fodder and barley two months before mating to strengthen them (II.II.13). Therefore, the cereal integration in an individual's diet might also depend on these factors.

Tracing the dietary intake of C_4 is more challenging when considering the values obtained from bulk collagen analyses performed on bone remains. For instance, individual MC 20160 exhibits a $\delta^{13}\text{C}$ value of -19.91‰ (see Section 4.3.1, Table 4.5). The signal of the contribution of C_4 plants to the diet in its later years is therefore attenuated. The bone collagen of five other individuals (MC 11146, MC 11159, MC 11217, MC 20165, MC 20168) provided values around -19‰, suggesting a possible consumption of C_4 fodder at some point in their lives. Consequently, the seasonal C_4 intake may have been masked in the multi-year values.

Sheep from the *Ceretan* settlement of Tossal de Baltarga had a purely C_3 diet. Neither bulk collagen nor sequential analyses registered supplements of C_4 plants in the diet. The $\delta^{13}\text{C}$ sequences of three of the four sheep individuals analysed - BTB 3031, BTB 3249 and BTB 3271 - display a very narrow amplitude, indicating minimal or no variation in the diet on a seasonal basis. As discussed above, this 'flattening' of the curve is due to anthropogenic

interference with the seasonal feeding habits of these individuals. For Individual BTB 3270, the increase in $\delta^{13}\text{C}$ values after its second summer corresponds to the consumption of carbon-enriched plants in a drier environment. Indeed, as previously discussed (see Sections 4.2.1 and 5.3), Individual 3270 practised seasonal altitudinal mobility towards lowland areas with different pastures. Its return to Cerdanya after the second winter caused a new change in feeding habits. Therefore, the decrease in $\delta^{13}\text{C}$ values is dictated by the change in altitude and, consequently, in pastures.

At Sant Esteve d'Olius, the $\delta^{13}\text{C}$ values obtained from bulk collagen and sequential analyses of the sheep sampled generally indicate a predominantly C_3 -based diet, with no significant seasonal variations. The collagen analysis performed on Individual O 484's mandible pointed to a contribution of C_4 plants to its diet (-18.70‰; see Section 4.3.1, Table 4.5), which was not reflected in the sequential analysis of its M_2 . Thus, dietary integration in Individual O 484 probably occurred after M_2 mineralisation. As in the case of Tossal de Baltarga, the $\delta^{13}\text{C}$ sequences generally display a narrow range that does not follow seasonal variations. Therefore, it is possible that in this case too, the herders supplemented the flock's diet with fodder and water.

Finally, collagen and sequence analyses indicate a generally plant-based C_3 diet for sheep from Turó de la Rovira. Two out of the three sheep analysed - TR 725 and TR 763 - exhibit wide and seasonally fluctuating $\delta^{13}\text{C}$ sequences (see Section 4.3.1, Figure 4.8). This indicates that their diet followed seasonal variations. The third individual - TR 831 - displays a variation in $\delta^{13}\text{C}$ values along the sequence, suggesting a change in feeding habits. As discussed above (see

Sections 4.2.1 and 5.3), this variation was due to seasonal short-range migration to wetter environments and, consequently, a change in pasture.

Another noteworthy aspect is the recording of high $\delta^{13}\text{C}$ values towards the end of TR 831's first summer, spent in the settlement (see Section 4.3.1, Figure 4.8). These values suggest a possible contribution of C_4 plants to its diet, although the data are by no means conclusive. As previously discussed, the reproduction and mobility strategies of the sheep from Turó de la Rovira suggest the existence of differentiated flock management and probably the division of the herd into two distinct groups. The data on the feeding habits of the flock reinforce this idea and further articulate the livestock management strategies employed in the *Layetán* settlement. Part of the flock, specifically those born in the spring, would have remained at Turó de la Rovira year-round. On the other hand, individuals born during the summer would have joined the practice of seasonal altitudinal mobility starting from their second year of life. Within this latter group, newborns too young to undertake seasonal migration during their first summer would have stayed in the settlement and received a supplement of C_4 plants in their fodder. This management, which includes the migration of a portion of the flock and the integration of C_4 plants into the diet, might have been influenced by the limited availability of pastures during the dry summer season. However, the limited number of individuals analysed makes it difficult to draw comprehensive conclusions.

The bulk collagen analysis performed on the mandible of Individual TR 831 yielded a $\delta^{13}\text{C}$ value of -18.76‰ (see Section 4.3.1, Table 4.5). This could indicate the integration of C_4 plants into its diet, confirming the results

from sequential analysis. An even higher value (-17.91‰) was observed in individual TR 819, suggesting the consumption of C_4 plants during its lifetime. Unfortunately, neither the M_2 nor the M_3 were recovered from this individual. It is therefore impossible to verify whether it was managed similarly to individual TR 831.

Concerning the results of the bulk collagen analyses, sheep generally exhibit $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values that fall in an intermediate position compared to those of the other *taxa* at all four sites. The feeding habits of sheep are compared below with those of goats, cattle, and pigs. The comparison allowed a better understanding of sheep diets and valuable information on the management of the other main domestic *taxa* analysed as a local baseline.

Sheep generally exhibit a more carbon-enriched and varied diet, characterised by a higher protein contribution compared to goats (see Section 4.3.1, Figure 4.9a). Despite both species consuming C_3 plants, sheep tend to adopt a grazing behaviour, whereas goats are inclined to browse and consume higher vegetation (Papachristou 1997; Bartolomé *et al.*, 1998; Balasse and Ambrose, 2005; Sanon *et al.*, 2007; Dwyer, 2009; Jiménez-Manchón *et al.*, 2023). It is plausible that sheep and goats shared pastures within the same flock. The difference in carbon values between the two species may be ascribed to their distinct feeding preferences. In each of the four settlements under consideration, goats predominantly consume C_3 plants, exhibiting a less diverse diet characterised by lower carbon and nitrogen content when compared to sheep (see Section 4.3.1, Figure 4.7).

This dietary disparity has been confirmed by Latin authors Columella and Varro. They point out that goats are more inclined to pasture in rugged areas and wooded glades, consuming shrubs and brambles (Colum. VII. VI.1; Varro II.III.6-7). In contrast, Columella's guidance on sheep advocates providing them access to abundant grassy pastures, while Varro recommends year-round outdoor grazing for the flock (Colum. VII.III.9; Varro II.II.7). Both authors agree on the importance of keeping sheep away from shrubs and bushes to prevent damage to their fleece. Additionally, Varro highlights the behavioural differences between the two caprine species. He notes that sheep display a docile and gregarious nature, whereas goats are inclined to disperse and move around in impervious environments (Varro II.II.3). Consequently, it is conceivable to imagine a mixed herd where both species have access to distinct plant resources, although pasturing in proximity. Finally, the exploitation of different secondary products obtained from both species should also be considered. While sheep were primarily exploited for meat and wool, goats were mainly used for milk and its derived products, such as cheese. The herders' different feeding strategies may correspond to distinct livestock practices and exploitation. The generally lower nitrogen values observed in goats compared to sheep across all four sites could suggest the incorporation of legumes as a dietary supplement. Notably, legumes offer high-quality hay and their nutrient-rich and plant protein content is known to exert positive effects on milk production and composition (Morand-Fehr and Sauvant, 1980; Harris *et al.*, 1996; Ahmed and Nour, 1997; Bonanno *et al.*, 2013).

The analysis of cattle remains reveals a general similarity in dietary patterns with sheep. Both species display similar variability in their $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, consistent with their grazing nature (see Section 4.3.1, Figure 4.9a). However, differences in dietary preferences between the two species emerge when considering the results obtained from each site (see Section 4.3.1, Figure 4.7). The shepherds fed caprines and cattle with different types of fresh vegetation and/or fodder. Indeed, the dietary requirements of each animal may vary depending on species, age, sex, and intended use. Therefore, it is not surprising to observe differences in the feeding habits of caprines and cattle within the same settlement, as well as among cattle from the four settlements. However, this livestock management approach implies the adoption of specialised and tailored feeding strategies for each species reared in the settlement. Furthermore, it requires access to a diverse array of pastures and forage resources to suit the specific needs of each animal.

Focusing on cattle, Iron Age Iberian herders employed different feeding strategies for this species in each settlement. At Mas Castellar de Pontós the introduction of C_4 plants in the cattle diet suggests a supplementary inclusion of cultivated cereals in their forage (see Section 4.3.1, Figure 4.7). The integration of C_4 plants into the livestock diet in the rural settlement is well attested by the results obtained through sequential isotope analysis on sheep teeth. Moreover, as previously outlined, the availability of residues from both winter and spring crops was guaranteed for a significant portion of the year (see Sections 4.3. and 5.2). Columella mentions the use of cereal chaff for cattle feed, emphasising millet as the primary option, followed by barley and wheat

(VI.III.3). The extensive presence of millet, a C_4 cereal, within the rural establishment, supports the feasibility of its utilisation for feeding the cattle at Mas Castellar de Pontós (Canal 2000; Canal 2002). However, Columella and Varro recommend grazing cattle in grassy, well-watered pastures (Colum. VI.III.2; Varro II.V.14). Additionally, in arid regions, Columella suggests supplementing their diet with legumes and hay meadows within the stables (VI.III.3).

At Tossal de Baltarga, both cattle and sheep predominantly consumed C_3 plants. However, the cattle's vegetal diet appears more homogeneous compared to those of sheep. This discrepancy may depend on the frequentation of different pastures for the two animals: cattle grazed in open pastures, whereas sheep pastured in the wooded areas surrounding the settlement, leading to a more varied consumption of plants.

The cattle from Sant Esteve d'Olius had a diet closely resembling that of sheep. Nonetheless, some individuals exhibit values suggestive of the consumption of plants from closed-canopy forests. According to Varro in Book II of *De re rustica*, cattle graze in wooded areas, consuming undergrowth and foliage (II.V.11). Hence, it cannot be ruled out that these plants provided a non-generalised contribution to their diet within the *Lacetan* settlement.

At Turó de la Rovira, the feeding habits of the cattle matched those of sheep. Nevertheless, their diet manifested greater variability. Some individuals consumed small amounts of plants from wooded areas, while others included C_4 plants in their dietary intake. It is feasible that the cattle were afforded unrestricted grazing around the *Laietan* settlement, feeding on both cultivated and uncultivated terrains.

In light of all these data, it is possible to suggest that the feeding strategies adopted by Iron Age Iberian herders for cattle varied between settlements, depending on the specific requirements and surrounding environment of each community. The limited collagen results available for the Bronze Age and Early Iron Age settlements in the north-east of the Iberian Peninsula indicate a more homogeneous scenario, characterised by the integration of C_4 plants into the cattle's diet (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021). On the other hand, the feeding habits of cattle during the Roman period indicate a predominant reliance on C_3 plants (Rissech *et al.* 2016; Salazar-García *et al.* 2022). The data obtained from the four Iron Age sites thus occupy an intermediate position between the earlier and later periods.

The $\delta^{13}C$ and $\delta^{15}N$ values of sheep and pigs, along with their variability, display no significant differences. However, pigs tend to exhibit less variability in $\delta^{13}C$ values than sheep (see Section 4.3.1, Figure 4.9a). Indeed, the pigs' alimentation in the four Iron Age settlements mainly consisted of C_3 plants, aligning with the dietary patterns observed in sheep. Additionally, their intake of animal protein was limited, suggesting a mildly omnivorous diet. Pigs from Sant Esteve d'Olius exhibit a slightly higher consumption of animal protein (see Section 4.3.1, Figure 7). However, the nitrogen values suggest that their diet was still predominantly herbivorous, with minimal contribution from culinary waste. Pigs were likely allowed to graze freely or semi-freely in the outdoors, rather than being reared in enclosures with a controlled diet.

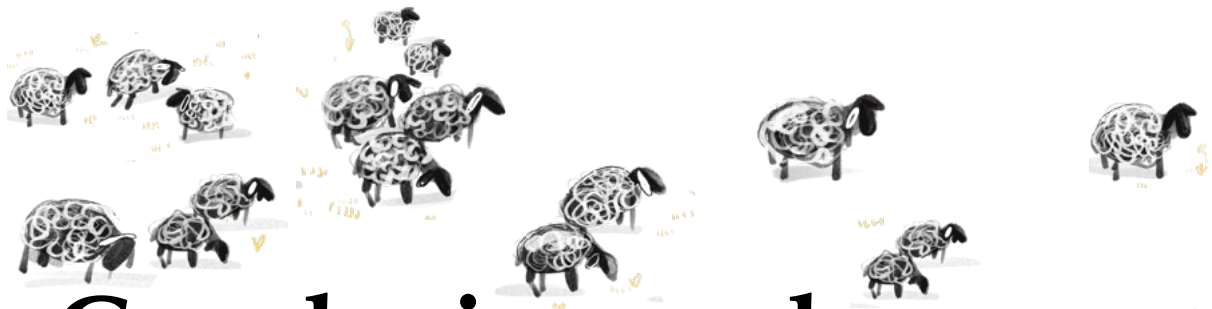
Both Columella and Varro refer to the use of legumes as pig fodder (Colum. VII.IX.9; Varro II.IV.6). The overall low

nitrogen values observed in suids' diet could be attributed to the inclusion of legumes, which may have mitigated possible signs of omnivorous behaviour. This hypothesis is supported by a previous study conducted by Lösch and colleagues (2006), which proposed the consumption of legumes by sheep, goats, and pigs from the Pre-Pottery Neolithic B site of Nevalı Çori as an explanation for the lower $\delta^{15}\text{N}$ values recorded in these *taxa*. On the other hand, the data available on Bronze and Early Iron Age Iberian pigs indicate a feeding strategy rich in animal protein (Grandal-d'Anglade *et al.* 2019; Albizuri *et al.* 2021). In contrast, the limited data available from the Roman Period suggest a significant shift in pig dietary habits, resulting in a generally lower but more varied animal protein content (Rissech *et al.* 2016; Salazar-García *et al.* 2022). Therefore, as in the case of cattle, the data on pigs' feeding strategies from the Iron Age Iberian settlements occupies an intermediate position in the intake of animal protein between the immediately earlier and later periods.

This study provides evidence of the seasonal consumption of C_4 plants by sheep at Mas Castellar de Pontós. The same feeding habit is also observed in cattle and probably horses, but it is unclear whether the consumption was continuous or sporadic for these two species. The results from both bone collagen and sequential dental analyses suggest that C_4 plants were also a supplement in the diet of cattle from Turó de la Rovira. Consequently, Iron Age Iberian shepherds supplemented the livestock's diet with C_4 cereals based on their specific necessities.

During prehistoric and protohistoric periods in the north-east or the entirety Iberian Peninsula, the integration of C_4 plants into sheep diet was not a common practice (Navarrete *et al.*

2019; Navarrete *et al.* 2023; Navarrete *et al.* 2024; Tejedor-Rodríguez *et al.* 2021; Martín *et al.* 2021; Sierra *et al.* 2021). Nevertheless, it is important to consider the geographic location of the Iberian Peninsula, which is situated in the southernmost area of Europe. This may have facilitated the thriving of C_4 plants in drier ecological niches. In the context of protohistoric times in the north-eastern Iberian Peninsula, Albizuri and colleagues (2021) suggest that dogs from the Can Roqueta site, dated between the Late Bronze Age and the Early Iron Age (1300 and 550 cal. BC), consumed C_4 cereals (millet), in alignment with human dietary practices. Furthermore, the data obtained from foxes also indicate consumption of C_4 cereals, suggesting a commensal relationship on the part of foxes during the Bronze Age. Finally, cattle also display values compatible with an integration of C_4 plants into their diet. Therefore, it cannot be ruled out that herbivorous species occasionally or seasonally consumed these plants. Further research could enhance our understanding of the consumption of C_4 plants by sheep and other livestock, providing a more comprehensive view.



Conclusion and future perspectives 6

6.1 General conclusion

This doctoral dissertation provided a considerable amount of biogeochemical data on sheep remains from four relevant Iron Age sites in the north-east of the Iberian Peninsula. Among the 535 sheep samples analysed, 43 were from bone remains, and 473 powdered and 19 sliced samples were from dental enamel. Additionally, 153 samples were analysed from bone remains of the main species recovered from the four sites studied. The stable isotope analyses allowed us to achieve the aim of this thesis, gaining novel insights into livestock management strategies adopted by Iron Age Iberian communities that have not been previously investigated. This study employed a multi-isotope approach to delineate, for the first time, on a seasonal level and through direct evidence, the in-life management of livestock during the protohistoric period.

Traditional zooarchaeological studies have already contributed to a characterisation of the advances in livestock husbandry during the Iron Age in the north-east of the

Iberian Peninsula. Despite this, the depth of investigation, the seasonal temporal dimension, and the amount of novel information on the lifetime management of sheep obtained through the multi-isotope approach in this doctoral thesis have marked a decisive step forward in the characterisation and comprehension of livestock husbandry during this period and in this region. This study highlights the enormous potential of data obtained through biogeochemical analyses to provide more detailed information on the economic and social dynamics of protohistoric societies and the interactions between Iberian communities and the environment.

The aim of the doctoral thesis was the *fil rouge* running through the articles that constitute this work. The four papers focus on the three specific objectives of this doctoral research (see Chapter 2), investigating the three crucial aspects of a husbandry system: reproduction patterns, mobility strategies, and livestock feeding habits. These three themes are closely interconnected but can be addressed independently. The results obtained from each one have

broadened the depth of interpretation and comprehension of livestock management and, in general, added new and relevant information on the economic and social dynamics within Iron Age Iberian communities.

Regarding the first aspect, sheep births were intentionally artificially manipulated by herders in two distinct ways, by interfering with the season and with the duration of the lambing period. On the other hand, the different mobile livestock strategies employed in the four settlements suggest the existence of a robust network of social and economic relations between Iberian societies in the 3rd century BC. Furthermore, the data obtained from Tossal de Baltraga and Sant Esteve d'Olius propose the image of a more interconnected Ibero-Pyrenean world with contemporary lowland communities. Finally, sheep feeding habits were subject to seasonal changes depending on pasture availability and settlement requirements. As a result, the four sites yielded different seasonal sheep feeding patterns. Furthermore, shepherds within each settlement provided individualised feeding strategies for each species. Hence, the Iron Age Iberian populations could manage their livestock efficiently by maximising their resources while catering to each animal's specific needs.

A detailed look at the four settlements analysed revealed four different sheep husbandry models. At Mas Castellar de Pontós, the favourable environmental conditions, the interlinking of the agricultural and pastoral calendars, and the demand for the availability of secondary products throughout the year allowed for the division of the flock, which was sedentary, into two groups with two different lambing periods. In addition, the sheep's feeding strategy involved the seasonal integration of cereals.

The harsh Pyrenean winter forced the herders of Tossal de Baltarga to intervene in the length of the sheep's birth period and their feeding habits. They supplemented C₃ fodder and water and moved part of the flock to lower altitudes during the winter.

Commercial and environmental reasons probably lay behind the livestock strategies observed at Sant Esteve d'Olius. The presence of sheep with external provenance, extended lambing period, and the integration of C₃ fodder and water reveal the attention paid to the herd in the *Lacetan* settlement.

Finally, the shepherds from Turó de la Rovira contrasted the dry Mediterranean summer with the seasonal integration of C₄ plants, likely cereals, and the seasonal migration of part of the flock. This mobile strategy may have led to the lamb births' extension into the summer.

These results indicate that during the Middle/Late Iron Age, although the Iberian communities shared common characteristics on husbandry practises, they were sovereign to practise self-sufficient livestock husbandry within each settlement. Despite this, livestock husbandry was complex on a local scale. Indeed, every community selected the strategies to adopt depending on the specific requirements of the settlement, considering the products to exploit, environmental conditions, economic needs, and political decisions. The shepherds had extensive knowledge and expertise in breeding, managing, and exploiting sheep and livestock in general. This ability is reflected in the extraordinary adaptability demonstrated by Iberian communities in facing climatic and geographical challenges.

The husbandry strategies uncovered by this doctoral project not only provide information on sheep care, growth, and maintenance by Iron Age Iberian communities. They also provide valuable and novel information on the organisation of pastoral communities and their socioeconomic strategies. The management patterns for herd reproduction, mobility, and feeding employed in each of the four settlements were planned in relation to each other, within a unique plan. Secondary products had to play a significant role in the economy of these populations, serving both for consumption and accumulation and for commercial exchange. The extension of the lambing period, the de-seasonalisation of the herd and the unidirectional movement of some sheep would confirm this hypothesis. To ensure the wellness of the flock and its production and reproduction, the availability of pasture or fodder throughout the year was essential. The seasonal integration of C_3 and C_4 plants and water into the diet and the seasonal altitudinal movements of the sheep ensured adequate nutrition even during the most extreme seasons.

The management and care of livestock evidenced by the results of this research required a considerable workforce, technical knowledge, time, and resources. It is plausible that agriculture, traditionally described as the main economic activity during this period, and husbandry were interconnected and perfectly integrated in their respective schedules within the Iron Age Iberian settlements. The huge technical effort required for such complex herd management inevitably suggests the presence of several people dedicated exclusively and specifically to monitoring and maintaining the flock throughout the year. This articulated management must have influenced

both the community organisation and the relationships established between settlements. The strategies employed in each settlement may have derived from a certain level of community decision-making. Likewise, the various mobility patterns documented in this dissertation suggest coordination between different pasture areas and their related communities.

To conclude, this doctoral thesis reveals for the first time the in-life livestock management during the Iberian period, inferring the sheep reproduction, mobility, and feeding strategies employed by different Iron Age communities. This research has finally provided an in-depth picture of livestock husbandry, recognising its importance in the economy of the Iberian communities in the north-east of the Iberian Peninsula.

6.2 Future perspectives

The results of this PhD dissertation broad and open up new perspectives in both methodological and historical research.

From a methodological point of view, the combination of the sequential analysis of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values and the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements confirmed the effectiveness and complementarity of these two proxies to investigate livestock movements across different altitudinal and geological areas. Although the combination is possible and final interpretations are better suited, a few more methodological efforts are still required to truly realise its full potential. Along these lines, it is important to insist on the need for future work to increase our knowledge on the timing of strontium assimilation in dental bioapatite compared to oxygen and carbon. This will allow more precise interpretation when sheep

track movements are investigated, even at a seasonal scale.

Moving to a historical perspective, the quantity and quality of the data collected also open new doors within the settlements studied in this doctoral thesis. Indeed, the isotopic analyses can be extended to the other main domestic species: goats, cattle, and pigs. In the case of goats, sequential analyses of M_2 and M_3 can provide information on their eventual mobility and seasonal feeding habits. As discussed in this dissertation, goats and sheep were likely part of the same mixed flock. Consequently, complementary research on goats would provide more detailed information on the management scheduling of this species, and especially, against sheep herding strategies.

Regarding cattle, the sequential analysis of dental enamel would allow a seasonal framing of the information obtained from the collagen analysis. At Mas Castellar de Pontós, it is necessary to define whether the integration of C_4 plants in cattle's diet was seasonal. At Tossal de Baltarga, it can be verified whether the carbon sequences exhibit a narrow amplitude as in sheep, indicating human intervention in seasonal feeding. Sequential analysis is required at Sant Esteve d'Olius to determine if the addition of plants from closed-canopy forests was seasonal (e.g. foddering strategy during the winter period). The cattle from Turó de la Rovira show an integration of both C_4 plants and plants from wooded areas in their diet. Sequential analysis would offer a seasonal interpretation of these feeding habits. This high temporal resolution is needed when deeper interpretation is sought and comprehensive understanding is desired on both subsistence and annual labour organization by Iberian communities.

Collagen analyses are required in cattle and pig remains from the Bronze Age to the Roman Period to validate the intermediate position of the two species of the Middle/Late Iron Age (bovids for carbon values and suids for nitrogen values) between the earlier and later periods.

Finally, it is imperative to extend the research to sheep remains from other settlements from the same chronology and geographical area. This broader approach would enable a multi-site analysis and verify the potential to formulate a more comprehensive model of the strategies employed in livestock management. Additionally, it is necessary to apply this type of research to the immediately preceding and succeeding periods to thoroughly investigate the development of the husbandry patterns adopted by the Iron Age Iberian communities.

This PhD dissertation not only contributes to the knowledge of livestock management strategies adopted by Iron Age Iberian communities, providing novel and fundamental historical information. Additionally, the results pave the way to new possibilities for investigation and strongly encourage the continuation of this research line, profiting from the large quantity and excellent preservation state of the faunal remains available for this chronotopic context.



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TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC) : A MULTI-ISOTOPE RESEARCH

Chiara Messina

Other publications

[1]. Colominas, L., Portillo, M., Morera, J., Oller, J., Berrocal-Barberà, A., Gallego-Valle, A., López-Bultó, O., **Messana, C.**, Morera, J., Oller, J., Tornero, C., Olesi, O. (2023). Livestock management at the Late Iron Age site of Baltarga (eastern Pyrenees): an integrated bio-geoarchaeological approach. *Archaeological and Anthropological Sciences*, 15 (10), 159. <https://doi.org/10.1007/s12520-023-01848-8>

[2]. Martín, P., **Messana, C.**, Di Simone, G., Allué, E., Expósito, I., Ollé, A., Vergès, J.M., Forgia, V. (2023). Animal husbandry in Sicilian prehistory: The zooarchaeological perspective from Vallone Inferno (Scillato, Palermo). *Journal of Archaeological Science: Reports*, 48, 103813.

[3]. Martín, P., **Messana, C.**, Di Simone, G. (2023). Allevamento e caccia nel massiccio delle Madonie (Sicilia) durante la preistoria e il periodo altomedievale: studi zooarcheologici nel sito di Vallone Inferno. In: Forgia, V., Ollé, A., Vergès, J.M. (eds.), *“Il riparo di Vallone Inferno (Madonie, Sicilia). Attività umana, ambiente e paesaggio negli ultimi settemila anni”*.

BAR INTERNATIONAL SERIES, 3154. BAR publishing, Oxford. <https://doi.org/10.30861/9781407361130>

[4]. Forgia, V., Ollé, A., Vergès, J.M., **Messana, C.**, Martín, P. (2023). Archeologia dei paesaggi montani: il caso studio di Vallone Inferno. In: Forgia, V., Ollé, A., Vergès, J.M. (eds.), *“Il riparo di Vallone Inferno (Madonie, Sicilia). Attività umana, ambiente e paesaggio negli ultimi settemila anni”*. BAR INTERNATIONAL SERIES, 3154. BAR publishing, Oxford. <https://doi.org/10.30861/9781407361130>

[5]. Rovira, M., Díez-Canseco, C., **Messana, C.**, (2023). Ellos también son lo que comen: la integración de los análisis de isótopos estables en zooarqueología. In: Carbonell Pastor, S., Fructuoso Cárcel, M., García López, A., Martín De La Sierra Pareja, P., Martínez Boix, J.L., Moya Soriano, E., Pastor Alameda, N., Ramón Baraza, P., Serna Martínez, I. (eds.), *“Periferias: desde los márgenes de la arqueología”*, JIA-lacant 2022 - Libro de Actas. <http://hdl.handle.net/10045/134216>

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Conference list

[1]. **Title:** Unveiling sheep altitudinal movements in the northeastern Iberian Peninsula during the 3rd c. BC: insights from a multi-isotope approach; **Congress:** 43rd Conference of the Association for Environmental Archaeology (AEA); **Authors:** **Messana, C.**, Tornero, C., Madgwick, R., Lamb, A., Evans, J., Colominas, L.; **Presentation type:** Oral presentation; **Place and date:** Tarragona (Spain), 24/11/2023 – 26/11/2023.

[2]. **Title:** Countering seasonal environmental constraints: resilient livestock strategies at the middle Iron Age site of Tossal de Baltarga (Cerdanya, eastern Pyrenees); **Congress:** AHEAD - Advances in Human Evolution, Adaptation & Diversity; **Authors:** **Messana, C.**, Tornero, C., Colominas, L.; **Presentation type:** Poster; **Place and date:** Tarragona (Spain), 15/11/2023 – 17/11/2023.

[3]. **Title:** Aproximació bio-geoarqueològica a l'estudi de la gestió ramadera al Tossal de Baltarga (la Cerdanya) (segle III a.n.e); **Congress:** VII Reunió Oikos de Bioarqueologia; **Authors:** Colominas, L., Portillo, M., Morera, J., Oller, J., Berrocal-Barberà,

A., Gallego-Valle, A., López-Bultó, O., **Messana, C.**, Sisa-López de Pablo, J., Tornero, C., Olesti, O.; **Presentation type:** Oral presentation; **Place and date:** Girona (Spain), 26/05/2023 – 27/05/2023.

[4]. **Title:** A glimpse of sheep seasonal vertical mobility during the middle Iron Age in the northeastern Iberian Peninsula: the case of Tossal de Baltarga (Cerdanya, eastern Pyrenees); **Congress:** Travelling Through time: New Perspectives, Methods and Challenges for Understanding Livestock Mobility in the Past; **Authors:** **Messana, C.**, Tornero, C., Colominas, L., Olesti, O.; **Presentation type:** Poster; **Place and date:** Aix-en-Provence (France), 26/05/2023 – 27/05/2023.

[5]. **Title:** An insight of sheep seasonal reproductive patterns on the north-eastern Iberian Peninsula before the Roman influence; **Congress:** UKAS 2022 - UK Archaeological Sciences Conference 2022; **Authors:** **Messana, C.**, Tornero, C., Colominas, L.; **Presentation type:** Poster; **Place and date:** Aberdeen (Scotland), 20/04/22 – 22/04/2022.

[6]. **Title:** An insight of livestock feeding habits on the northeastern Iberian Peninsula before the Roman influence: The case of the late Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain); **Congress:** 10° Convegno Nazionale di Archeozoologia (AIAZ); **Authors:** Messina, C., Tornero, C., Colominas, L., Pons, E.; **Presentation type:** Poster; **Place and date:** Siena (Italy) - Virtual, 03/11/2021 – 006/12/2021.

[7]. **Title:** An insight of sheep's seasonal reproductive pattern on the northeastern Iberian Peninsula before the Roman influence: The Case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain); **Congress:** 9th Postgraduate ZooArchaeology Forum (PZAF); **Authors:** Messina, C., Tornero, C., Colominas, L., Pons, E.; **Presentation type:** Presentación oral; **Place and date:** Belgrade (Serbia) - Virtual, 25/06/2021 – 27/06/2021.

[8]. **Title:** Reconstruction of pastoral systems and livestock practices through isotopic analyses: the case of the Iron Age rural settlement of Mas Castellar de Pontós (Girona, Spain); **Congress:** BECC – Bioarchaeology Early Career Conference 2021; **Authors:** Messina, C., Tornero, C., Colominas, L., Pons, E.; **Presentation type:** Poster; **Place and date:** Glasgow (Scotland) - Virtual, 25/03/2021 – 28/03/2021.

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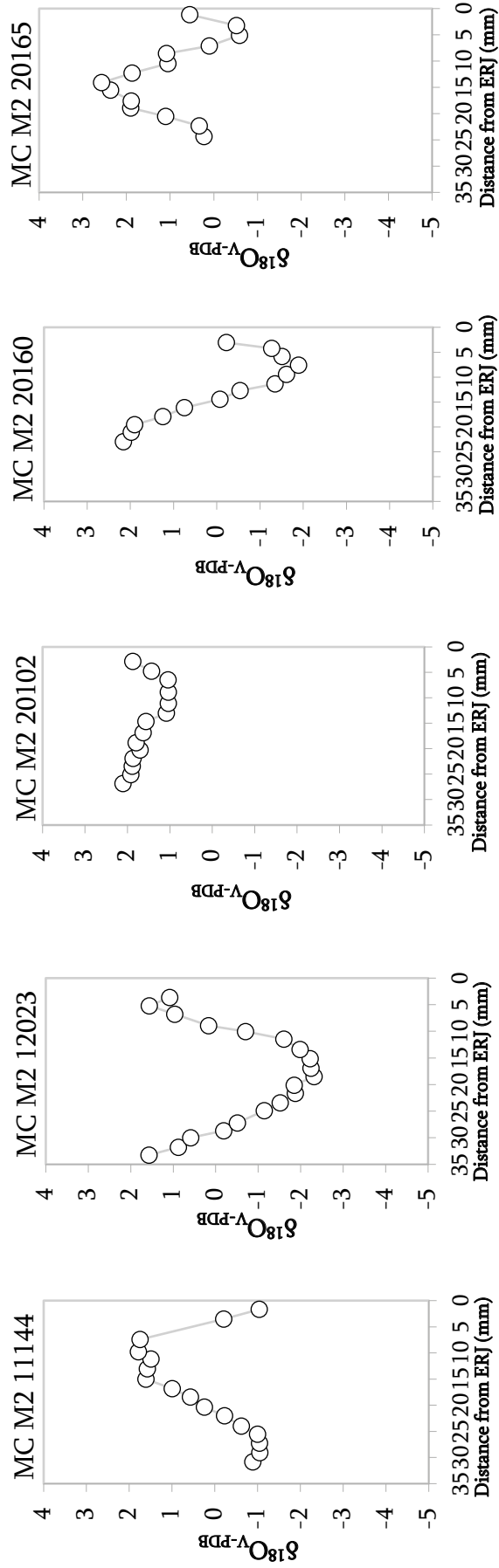
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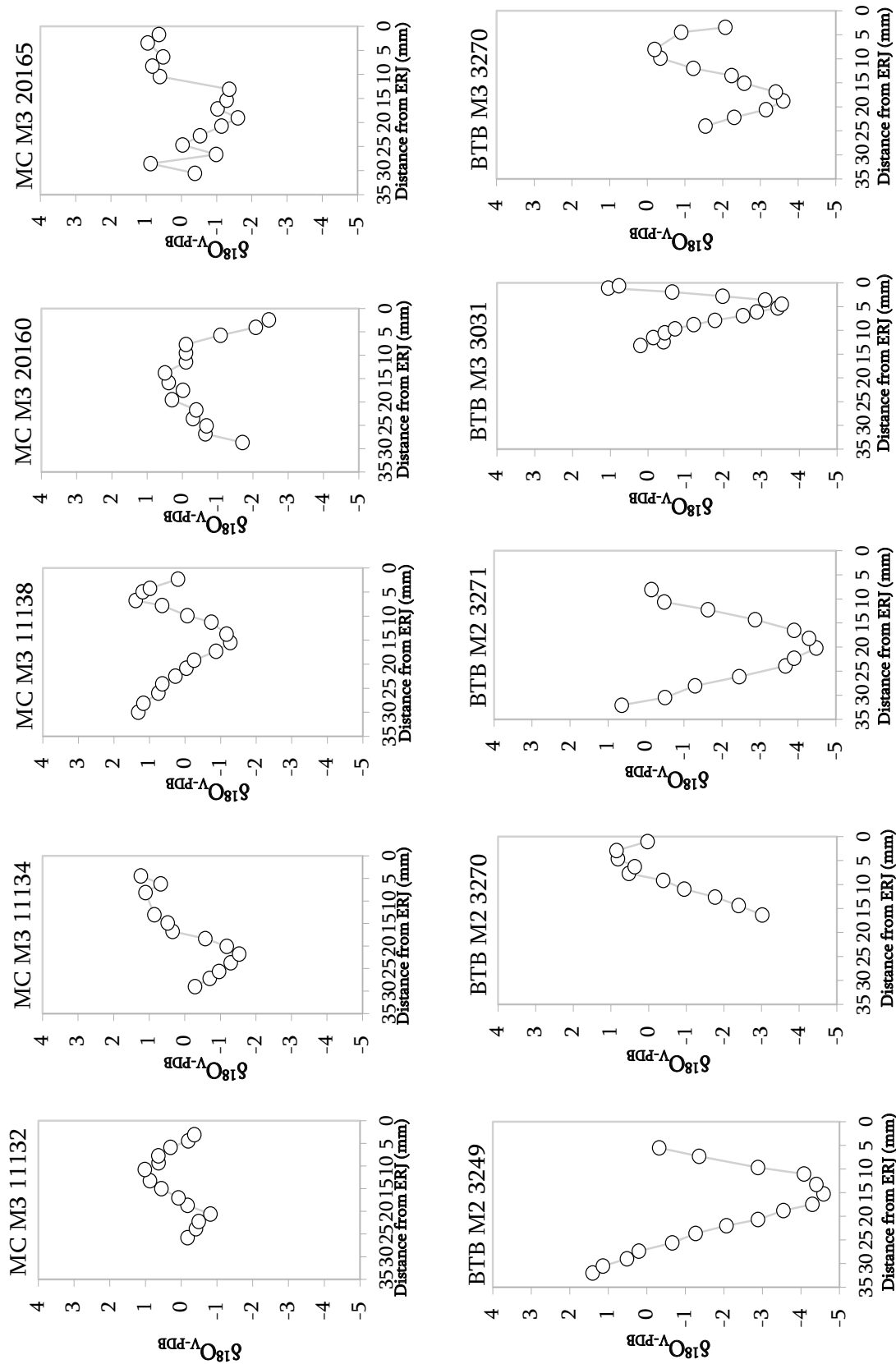
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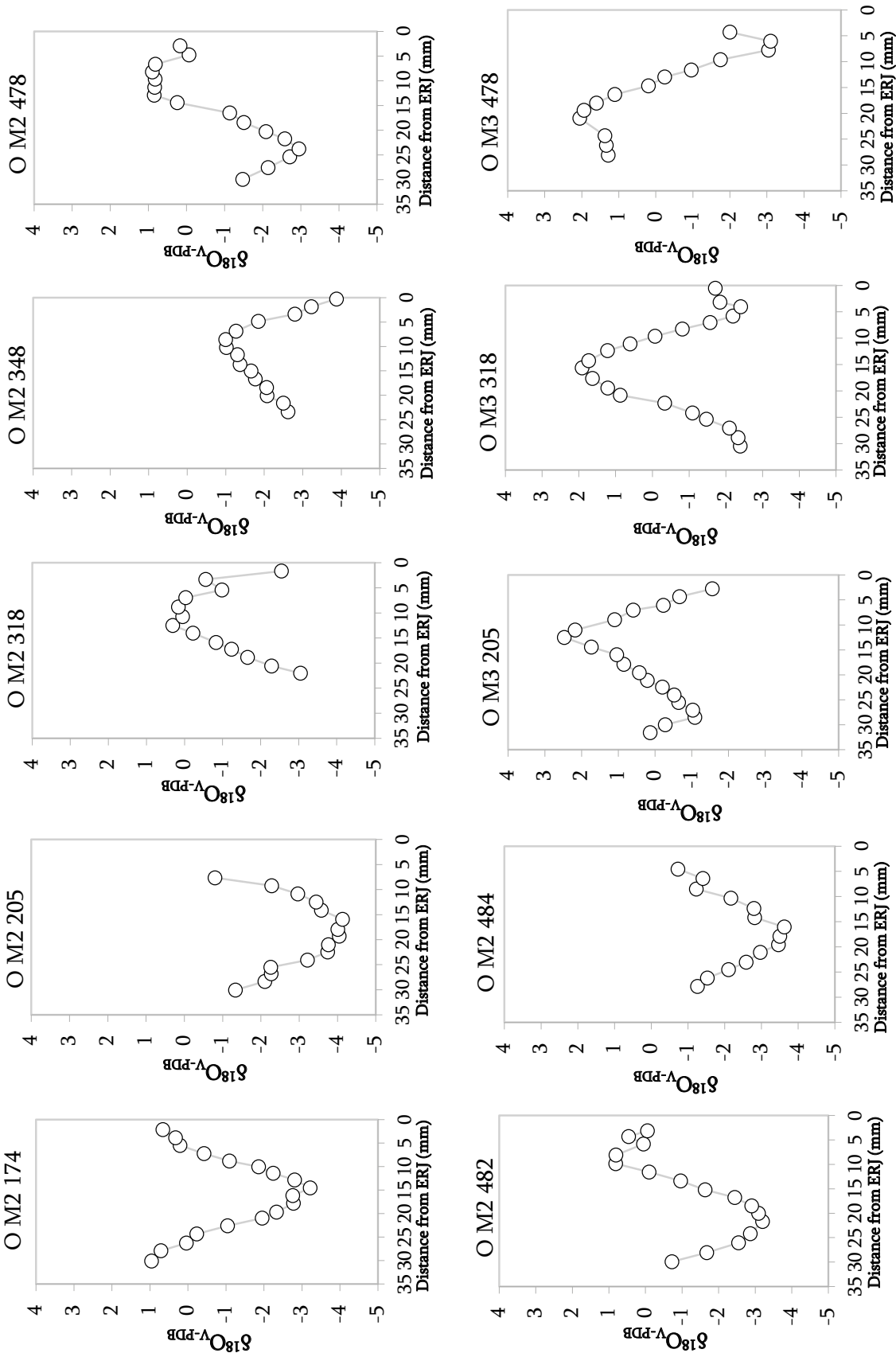
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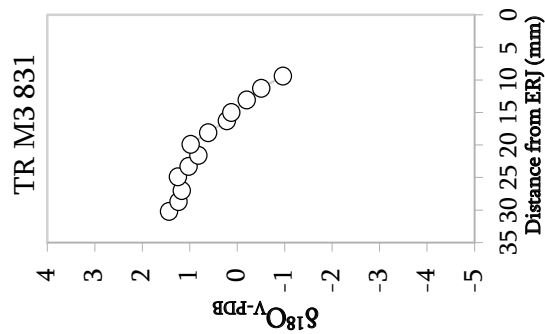
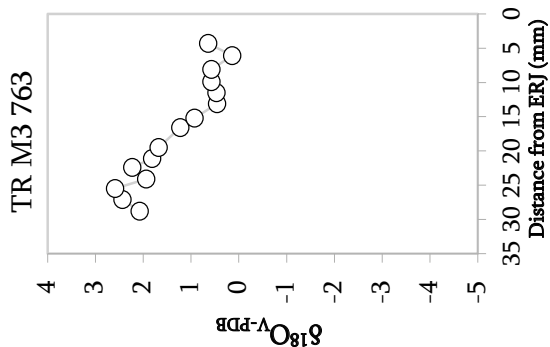
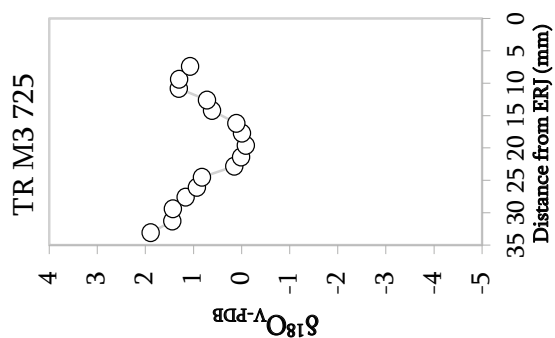
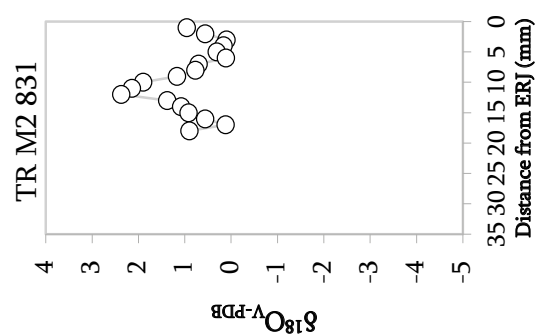
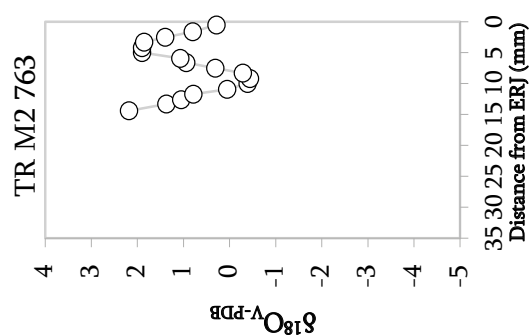
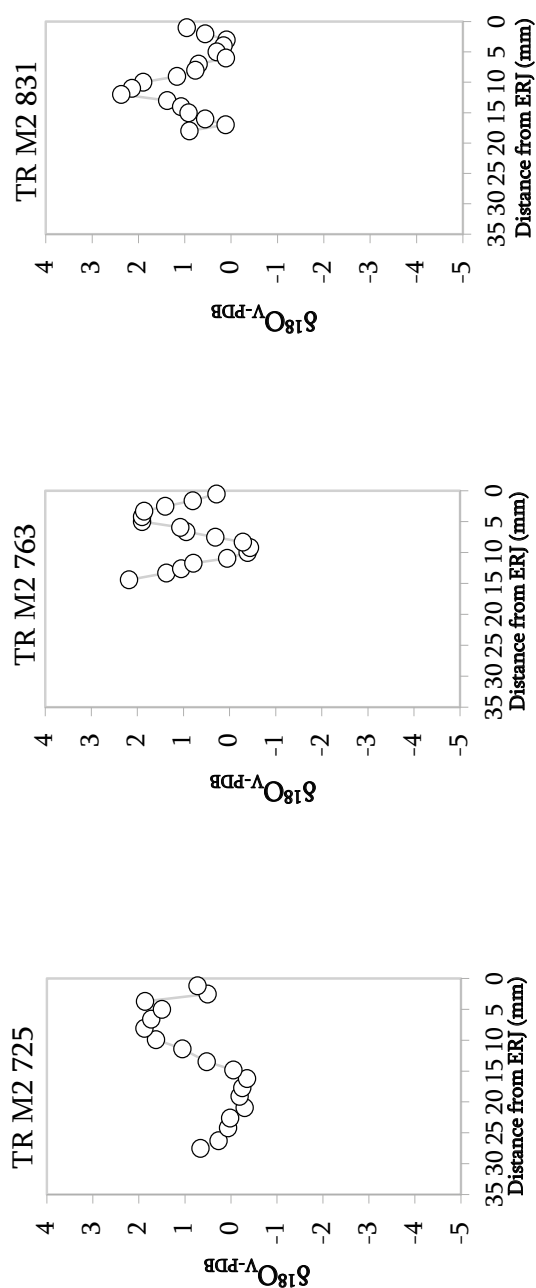
Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula
Archaeological and Anthropological Sciences
Chiara Messina*, Carlos Tornado*, Lidia Colominas
* corresponding authors
Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain (ES)
Universitat Rovira i Virgili (URV), Departament d’Història i Història de l’Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain (ES)
Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193 Bellaterra, Spain (ES)
cmessana@iphes.cat
Carlos.Tornado@uab.cat

Sequential $\delta^{18}\text{O}_{\text{V-PDB}}$ values measured on enamel bioapatite of sheep second and third molars.









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Chiara Messina*, Carlos Tornero*, Lidia Colominas
* corresponding authors
Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain (ES)
Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain (ES)
Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193 Bellaterra, Spain (ES)
cmessana@iphes.cat
Carlos.Tornero@uab.cat

$\delta^{18}\text{O}$ values in enamel bioapatite samples from sheep lower second (M_2) and third molars (M_3).

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
MC M2	30.84	-0.89	MC M2	33.25	1.57	MC M2	26.86	2.10	MC M2	22.98	2.16
11144	29.09	-1.05	12023	31.76	0.88	20102	25.08	1.92	20160	21.10	1.98
	27.28	-1.04		30	0.59		23.44	1.89		19.57	1.90
	25.57	-1.00		28.67	-0.19		21.93	1.87		17.93	1.25
	24.02	-0.62		27.18	-0.51		20.23	1.70		16.15	0.74
	22.02	-0.22		24.91	-1.14		18.83	1.79		14.46	-0.08
	20.38	0.24		23.41	-1.52		16.83	1.63		12.75	-0.54
	18.44	0.57		21.62	-1.88		14.63	1.56		11.39	-1.35
	16.86	1.00		20.12	-1.85		13	1.08		9.47	-1.62
	15.03	1.61		18.50	-2.32		11.07	1.04		7.63	-1.89
	13.06	1.58		16.89	-2.24		8.86	1.04		5.89	-1.51
	11.17	1.49		15.14	-2.22		6.48	1.04		4.25	-1.27
	9.76	1.79		13.38	-1.99		4.79	1.43		3.08	-0.22
	7.45	1.75		11.45	-1.61		2.87	1.87			
	3.52	-0.21		10.05	-0.70						
	1.68	-1.04		8.94	0.17						
				6.76	0.96						
				5.19	1.56						
				3.64	1.09						

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
MC M2 20165	24.36	0.22	MC M3	25.79	-0.17	MC M3	29.03	-0.29	MC M3	30	1.32
	22.35	0.33	11132	23.80	-0.41	11134	27.16	-0.70	11138	28.12	1.17
	20.52	1.10		22.22	-0.49		25.66	-0.96		25.99	0.75
	18.91	1.90		20.59	-0.81		23.73	-1.29		24.09	0.64
	17.63	1.89		18.66	-0.18		21.77	-1.53		22.46	0.27
	15.53	2.36		17	0.08		20.07	-1.18		20.84	-0.03
	14.10	2.57		14.96	0.56		18.33	-0.57		19.15	-0.25
	12.31	1.87		13.22	0.88		16.73	0.34		17.33	-0.87
	10.48	1.05		10.77	1.02		14.86	0.48		15.49	-1.27
	8.55	1.08		9.27	0.64		13.03	0.85		13.73	-1.17
	7.10	0.10		7.74	0.64		8.16	1.11		11.26	-0.74
	5.08	-0.59		5.90	0.30		6.20	0.68		9.94	-0.06
MC M3 20160	3.26	-0.52		4.45	-0.20		4.43	1.24		7.78	0.65
	1.16	0.55		3.08	-0.37					6.76	1.39
										4.93	1.19
										4.24	0.99
										2.32	0.20
MC M3 20160	28.68	-1.70	MC M3	30.54	-0.39						
	26.83	-0.64	20165	28.53	0.87						
	25.13	-0.68		26.63	-0.99						
	23.59	-0.30		24.69	-0.04						
	21.72	-0.39		22.73	-0.54						
	19.53	0.30		20.75	-1.14						
	17.50	-0.01		19.02	-1.60						
	15.84	0.40		17.19	-1.03						
	13.77	0.50		15.33	-1.29						
	11.41	-0.10		13.09	-1.36						
	9.52	-0.10		10.43	0.61						
	7.68	-0.10		8.28	0.82						
MC M3 20160	5.75	-1.08		6.38	0.51						
	4.03	-2.08		3.46	0.95						
	2.40	-2.45		1.70	0.63						

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
BTB M2 3249	31.99	1.41	BTB M2	16.33	-3.02	BTB M2	32.04	0.63	BTB M3	24.02	-1.54
	30.50	1.14	3270	14.38	-2.39	3271	30.46	-0.50	3270	22.16	-2.31
	29.01	0.51		12.59	-1.76		28.03	-1.29		20.59	-3.14
	27.38	0.21		10.95	-0.95		26.12	-2.46		18.79	-3.60
	25.64	-0.66		9.15	-0.38		23.92	-3.68		16.88	-3.41
	23.62	-1.27		7.69	0.53		22.33	-3.90		15.07	-2.57
	22	-2.07		6.26	0.37		20.19	-4.49		13.47	-2.24
	20.66	-2.89		4.63	0.81		18.20	-4.30		11.96	-1.22
	18.79	-3.55		2.93	0.85		16.55	-3.90		9.85	-0.34
	17.49	-4.30		1.03	0.03		14.33	-2.88		8.04	-0.19
	15.26	-4.59					12.24	-1.63		4.50	-0.90
	13.25	-4.40					10.63	-0.48		3.46	-2.07
	11.03	-4.08					8.08	-0.14			
	9.67	-2.88									
BTB M3 3031	27.4	0.20									
	25.67	-0.41									
	23.95	-0.14									
	21.78	-0.44									
	20.01	-0.71									
	18.54	-1.21									
	16.68	-1.77									
	14.75	-2.51									
	13.08	-2.88									
	11.39	-3.44									
	9.97	-3.54									
	8.40	-3.10									
	6.71	-1.98									
	5.04	-0.64									
	3.06	1.06									
	1.69	0.77									

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
O M2 174	30.10	0.95	O M2 205	30.05	-1.34	O M2 318	22.02	-3.0488946	O M2 348	23.38	-2.61
	27.94	0.71		28.31	-2.10		20.59	-2.2885628		21.64	-2.50
	26.27	0.04		26.81	-2.27		18.88	-1.6583176		20.10	-2.07
	24.34	-0.23		25.49	-2.26		17.22	-1.2389838		18.44	-2.06
	22.63	-1.04		24.05	-3.22		15.90	-0.8282959		16.68	-1.76
	20.98	-1.96		22.44	-3.75		14.04	-0.2235123		15.01	-1.65
	19.72	-2.33		21.02	-3.76		12.50	0.30764396		13.71	-1.37
	17.81	-2.78		19.29	-4.04		10.72	0.0474246		11.70	-1.30
	16.18	-2.76		17.95	-4.01		8.83	0.1556905		10.23	-1.02
	14.55	-3.22		15.94	-4.13		6.95	-0.0330779		8.58	-1.00
	12.86	-2.81		14.10	-3.58		5.42	-0.9877044		6.86	-1.27
	11.42	-2.25		12.47	-3.44		3.31	-0.5587321		4.84	-1.84
	10.04	-1.86		10.85	-2.97		1.67	-2.5495908		3.38	-2.79
O M2 478	8.83	-1.10		9.22	-2.28					1.88	-3.22
	7.23	-0.43		7.64	-0.80					0.26	-3.88
	5.49	0.21									
	3.87	0.33							O M3 205	31.61	0.14
	2.13	0.66								30.02	-0.28
										28.51	-1.08
										27.08	-1.03
										25.56	-0.64
										24.06	-0.52
										22.46	-0.20
										21.13	0.21
										19.57	0.43
										17.91	0.85
O M2 482	29.96	-1.48	O M2 482	29.92	-0.72	O M2 484	27.88	-1.26		16	1.04
	27.61	-2.15		28.07	-1.68		26.19	-1.52		14.42	1.74
	25.41	-2.71		26.07	-2.54		24.54	-2.10		12.51	2.47
	23.79	-2.95		24.20	-2.87		23.04	-2.59		11.02	2.17
	21.78	-2.58		21.69	-3.20		21.08	-2.97		8.97	1.10
	20.31	-2.08		20	-3.09		19.56	-3.46		7.05	0.59
	18.45	-1.50		18.52	-2.91		17.91	-3.50		6.10	-0.23
	16.52	-1.14		16.79	-2.44		16.04	-3.62		4.37	-0.67
	14.41	0.24		15.20	-1.63		14.16	-2.82		2.78	-1.56
	12.92	0.85		13.40	-0.96		12.38	-2.79			
	11.29	0.83		11.57	-0.10		10.31	-2.17			
	9.64	0.82		9.86	0.82		8.52	-1.23			
	8.18	0.90		8.09	0.81		6.42	-1.41			
O M2 484	6.66	0.81		5.86	0.05		4.53	-0.73			
	4.75	-0.07		4.30	0.46						
	2.92	0.17		3.13	-0.06						

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
O M3 318	30.47	-2.39	O M3 478	28.08	1.28
	28.89	-2.34		26.21	1.34
	27.07	-2.10		24.36	1.38
	25.36	-1.47		20.97	2.06
	24.20	-1.09		19.44	1.94
	22.33	-0.33		18.04	1.61
	20.81	0.87		16.34	1.11
	19.44	1.22		14.67	0.20
	17.61	1.63		12.95	-0.24
	15.63	1.91		11.61	-0.96
	14.27	1.74		9.62	-1.75
	12.37	1.22		7.78	-3.04
	11.07	0.60		6.04	-3.10
	9.61	-0.08		4.30	-2.00
	8.27	-0.82			
	7.01	-1.57			
	5.81	-2.19			
	4.03	-2.40			
	3.16	-1.84			
	0.52	-1.71			

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$
TR M2 725	27.79	0.66	TR M2 763	28.69	2.18	TR M2 831	30.30	0.96	TR M3 725	33.17	1.89
	26.70	0.27		26.92	1.37		28.54	0.56		31.27	1.44
	24.98	0.07		25.25	1.05		26.79	0.10		29.63	1.43
	23.12	0.01		23.92	0.79		25.11	0.16		28.24	1.16
	21.29	-0.30		22.10	0.05		23.23	0.31		26.53	0.93
	19.73	-0.19		20.46	-0.39		21.61	0.11		24.95	0.82
	18.33	-0.25		18.53	-0.44		19.94	0.70		23.03	0.15
	16.67	-0.35		16.81	-0.29		18.14	0.77		21.71	0.01
	15.11	-0.05		14.89	0.31		16.63	1.17		19.88	-0.09
	13.72	0.53		13.36	0.94		15.15	1.90		18.11	-0.01
	12.30	1.06		11.89	1.07		13.58	2.14		16.07	0.11
	10.32	1.63		9.93	1.90		12.09	2.37		14.07	0.62
	8.73	1.88		8.35	1.90		10.61	1.38		12.51	0.72
	7.33	1.73		6.66	1.85		8.57	1.08		10.49	1.31
	5.20	1.50		5.05	1.40		7.47	0.92		8.76	1.30
	3.93	1.87		3	0.80		5.85	0.56		6.96	1.07
	2.59	0.50		1.85	0.28		3.77	0.12			
	1.38	0.73									
TR M3 763	28.81	2.08	TR M3 831	30.55	1.44						
	27.15	2.44		29.03	1.24						
	25.77	2.59		27.24	1.16						
	24.26	1.94		25.42	1.25						
	22.84	2.23		23.76	1.03						
	21.46	1.81		22.19	0.82						
	19.75	1.68		20.63	0.98						
	16.63	1.23		18.75	0.61						
	15.33	0.93		17.28	0.22						
	13.49	0.46		15.47	0.13						
	11.75	0.47		13.10	-0.20						
	10.10	0.57		11.45	-0.51						
	8.06	0.57		9.06	-0.96						
	6.38	0.14									
	3.77	0.64									

Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula

Archaeological and Anthropological Sciences

Chiara Messana*, Carlos Tornero*, Lidia Colominas

* corresponding authors

Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades

URV (Edifici W3), 43007 Tarragona, Spain (ES)

Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, Avinguda de Catalunya 35, 43002

Tarragona, Spain (ES)

Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193

Bellaterra, Spain (ES)

cmessana@iphes.cat

Carlos.Tornero@uab.cat

Lower second molars (M₂): results from the calculation of the best fit (by method of least squares) for combined variation of X (period), A (amplitude), x₀ (delay) and M (mean). The Pearson's correlation coefficient (R) is also

Specimens	X (mm)	A (%)	x ₀ (mm)	M (%)	R	x ₀ /X
MC M2 11144	29.17	1.4	12.70	0.3	0.988	0.44
MC M2 12023	23.59	1.9	4.50	-0.7	0.987	0.19
MC M2 20102	28.97	0.5	23.26	1.5	0.985	0.80
MC M2 20160	28.94	2.0	22.20	0.2	0.998	0.77
MC M2 20165	21.67	1.4	15.26	1.1	0.967	0.70
Mean	26.47	1.4	15.6	0.5	Max	0.80
Δ	3.57	0.60	7.65	0.82	Min	0.19
BTB M2 3249	26.45	2.5	2	-2.2	0.992	0.08
BTB M2 3270	27.13	2	4.58	-1.2	0.994	0.17
BTB M2 3271	25.63	2.2	7.12	-2.3	0.995	0.28
Mean	26.40	2.2	4.6	-1.9	Max	0.28
Δ	0.75	0.26	2.56	0.61	Min	0.08
O M2 174	28.02	1.9	1.60	-1.1	0.994	0.06
O M2 205	25.46	1.4	5.32	-2.9	0.947	0.21
O M2 318	22.85	1.5	10.91	-1.0	0.977	0.48
O M2 348			Not modelling			
O M2 478	28.65	1.9	9.69	-0.9	0.994	0.34
O M2 482	28.46	2.0	7.38	-1.3	0.990	0.26
O M2 484	26.92	1.3	4.04	-2.2	0.982	0.15
Mean	26.73	1.7	6.5	-1.6	Max	0.48
Δ	2.24	0.31	3.52	0.81	Min	0.06
TR M2 725	26.58	1.1	7.20	0.6	0.967	0.27
TR M2 763	21.25	1.2	8.27	0.7	0.989	0.39
TR M2 831	22.40	0.9	13.12	0.9	0.956	0.59
Mean	23.41	1.1	9.5	0.8	Max	0.59
Δ	2.80	0.17	3.16	0.15	Min	0.27

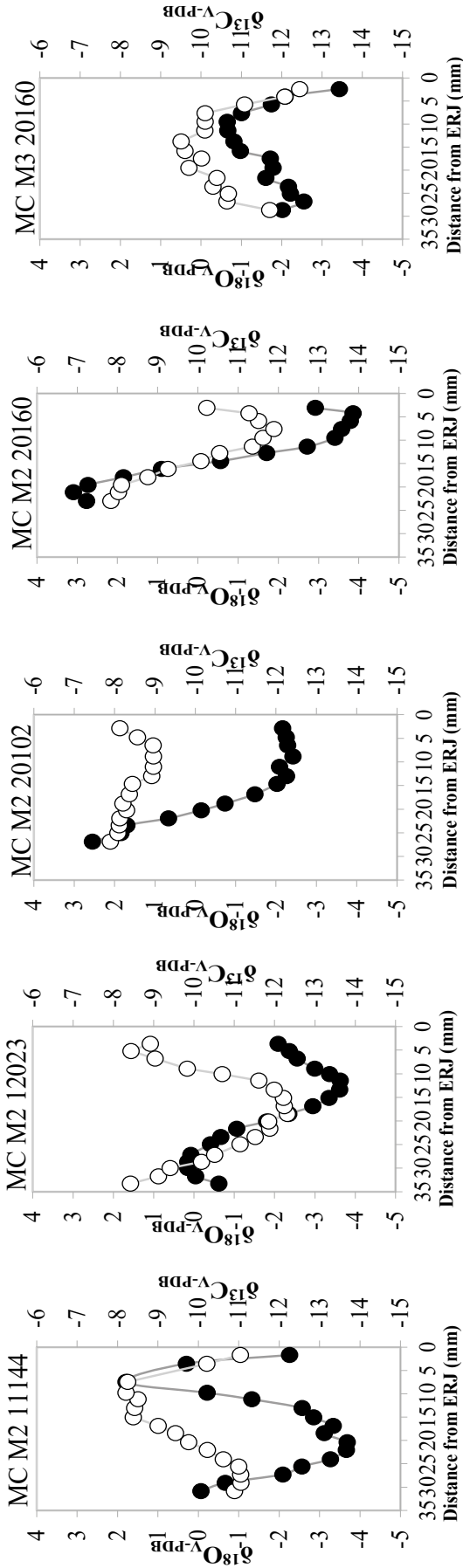
Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula
Archaeological and Anthropological Sciences
Chiara Messina*, Carlos Torno*, Lúdia Colominas
* corresponding authors
Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain (ES)
Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain (ES)
Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193 Bellaterra, Spain (ES)
cmessana@iphes.cat
Carlos.Torno@uab.cat

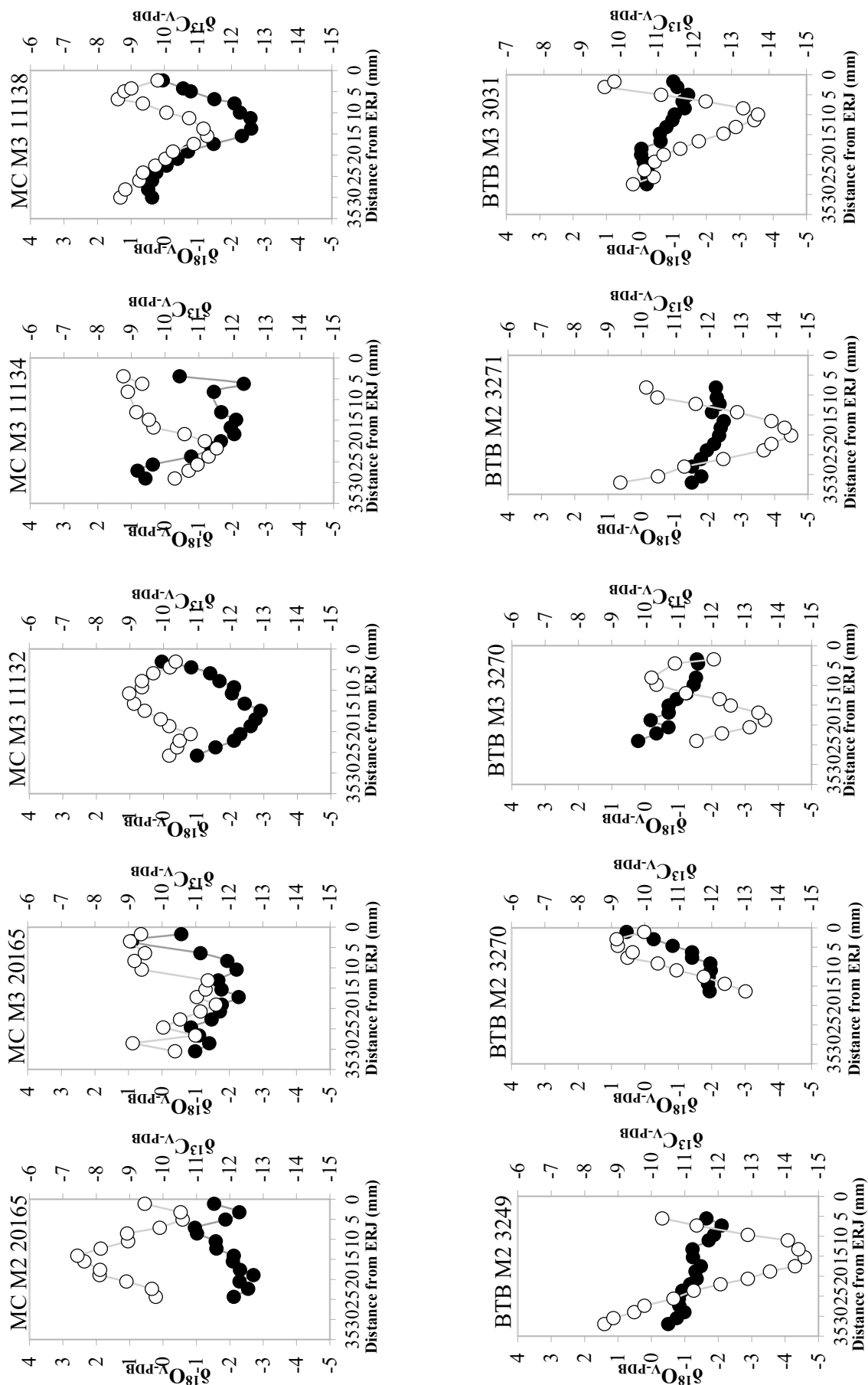
Lower third molars (M₃): results from the calculation of the best fit (by method of least squares) for combined variation of X (period), A (amplitude), x₀ (delay), M (mean), slope (p), signal attenuation (xA) and lateral shift (xB) of the amplitude and gradation of the period (b). The Pearson's correlation coefficient (R) is also

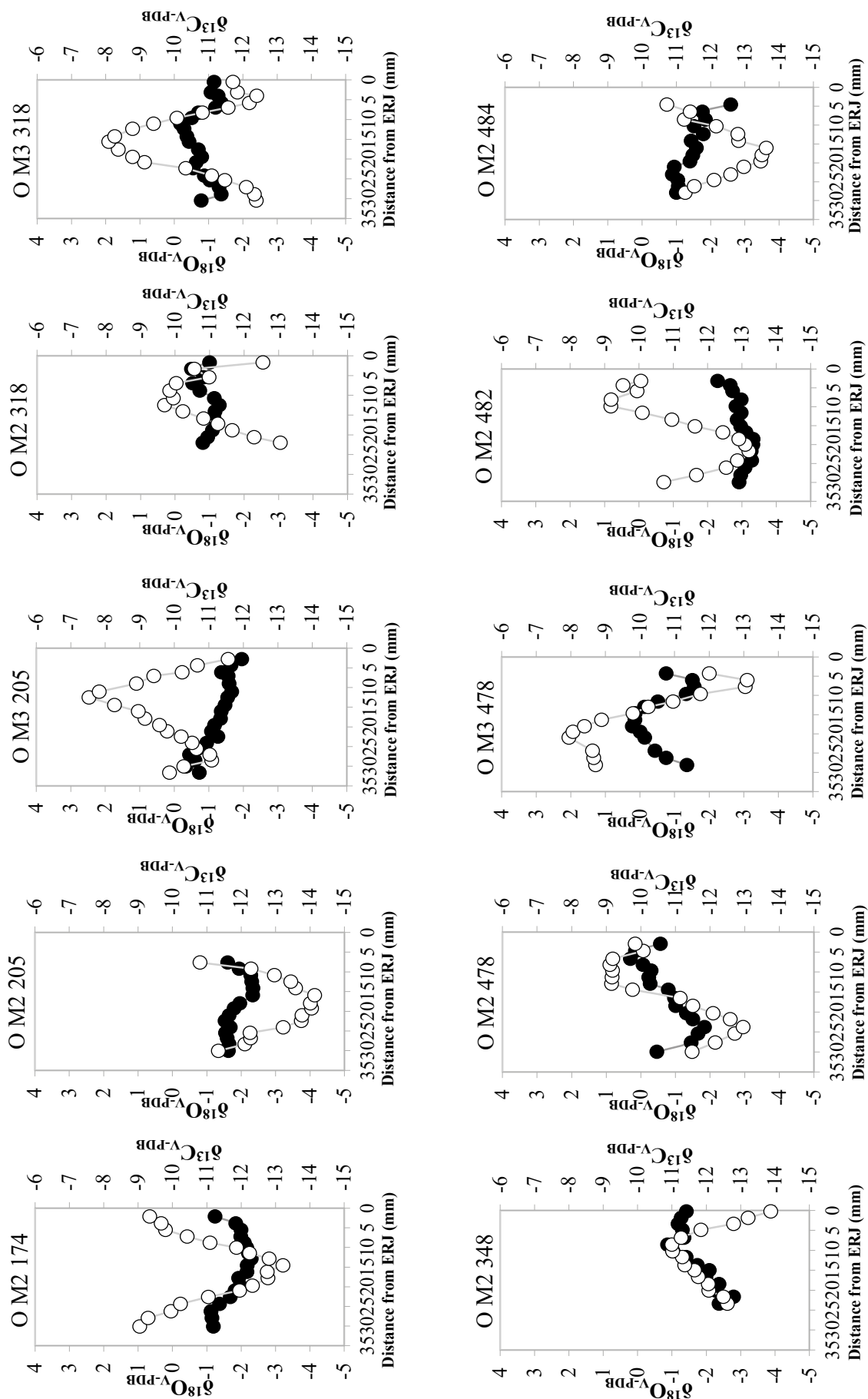
Specimens	X (mm)	A (%)	x ₀ (mm)	M (%)	p (%)	x _A (mm)	x _B (mm)	b	R	x ₀ /Xreal
MC M3 11132	20.22	0.7	11.22	0.2	0	100000000	5.1235E-08	0.07018579	0.989	0.52
MC M3 11134	25.47	1.3	10.34	0	0	100000000	6.0218E-06	0	0.984	0.41
MC M3 11138	13.65	1.3	5.61	0	0	100000000	6.1362E-06	0.27576517	0.993	0.32
MC M3 20160					Not modelling					
MC M3 20165	8.97	1.3	8.07	-0.3	0	1000000	3.2603E-06	0.49474983	0.957	0.60
Mean	17.08	1.2	8.8	0.0	0	750250000	3.8674E-06	0.21017520	Max	0.60
Δ	7.25	0.28	2.51	0.21	0	499500000	2.8706E-06	0.22290163	Min	0.32
BTB M3 3031	7.07	2.3	2.60	-1.1	0	1000000	-9.328E-06	0.79547813	0.991	0.20
BTB M3 3270	18.41	1.7	8.14	-1.8	0	1000000	-9.194E-07	0.08483825	0.989	0.41
Mean	12.74	2.0	5.4	-1.4	0	1000000	-5.124E-06	0.44015819	Max	0.41
Δ	8.02	0.39	3.92	0.52	0	0.00	5.9457E-06	0.50249828	Min	0.20
O M3 205	17.57	1.5	12.48	0.6	0	1000000	-2.33E-07	0.44970251	0.966	0.49
O M3 318	24.09	2.1	15.84	-0.2	0	1000000	0.0001057	0.10438693	0.995	0.60
O M3 478	21.32	2.4	21.32	-0.6	0	1000000000	-6.014E-05	1.19790993	0.994	0.45
Mean	20.99	2.0	16.5	-0.1	0	334000000	1.5107E-05	0.58399979	Max	0.60
Δ	3.27	0.48	4.47	0.60	0	576772919	8.3977E-05	0.55899460	Min	0.45
TR M3 725	15.94	0.7	9.17	0.6	0	1000000	-8.846E-05	0.19009089	0.985	0.48
TR M3 763	37.90	1.0	29.18	1.3	0	1000000	-8.579E-05	0.5	0.968	0.51
TR M3 831					Not modelling					
Mean	26.92	0.9	19.2	1.0	0	1000000.0	-8.713E-05	0.3	Max	0.51
Δ	15.52	0.20	14.15	0.51	0	0.00	1.8827E-06	0.22	Min	0.48

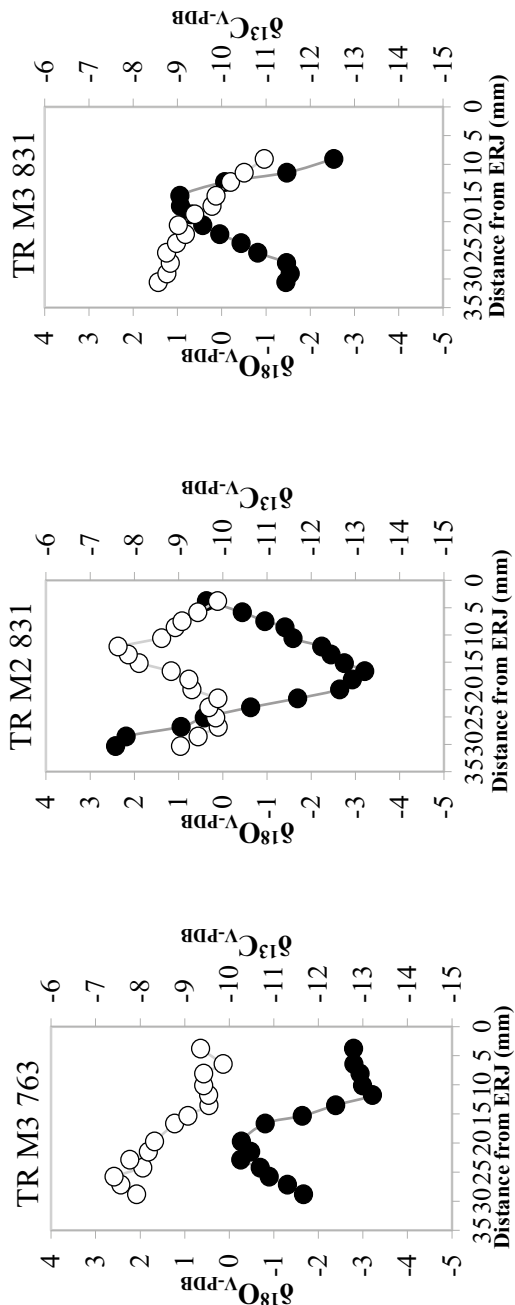
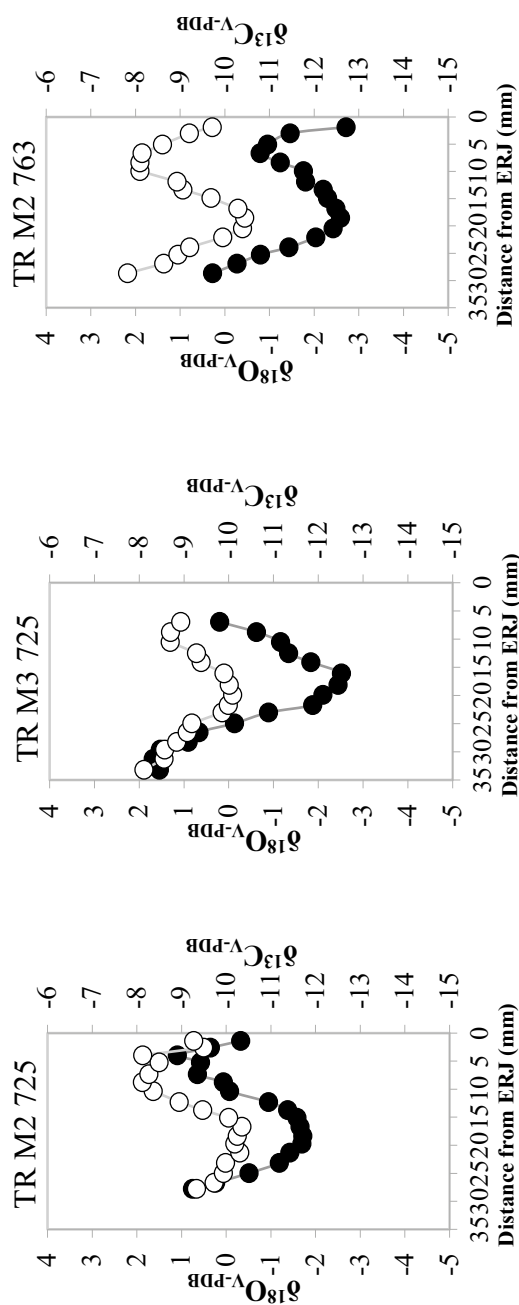
Between valleys, plateaus, and mountains: unveiling livestock altitudinal mobility in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope approach
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Supplementary Figure 1. Sequential $\delta^{18}\text{O}_{\text{V-PDB}}$ (white dots) and $\delta^{13}\text{C}_{\text{V-PDB}}$ (black dots) values measured along the tooth crown of the lower second (M_2) and third (M_3) sheep molars.









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Supplementary Table 1. $\delta^{18}\text{O}_{\text{V-PDB}}$ and $\delta^{13}\text{C}_{\text{V-PDB}}$ values measured on enamel bioapatite of sheep lower second (M_2) and third (M_3) molars.

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M2	30.84	-0.89	-10.06	MC M2	33.25	1.57	-10.62	MC M2	26.86	2.10	-7.45
11144	29.09	-1.05	-10.66	12023	31.76	0.88	-10.04	20102	25.08	1.92	-8.16
	27.28	-1.04	-12.09		30.00	0.59	-9.85		23.44	1.89	-8.30
	25.57	-1.00	-12.56		28.67	-0.19	-9.85		21.93	1.87	-9.34
	24.02	-0.62	-13.27		27.18	-0.51	-9.92		20.23	1.70	-10.15
	22.02	-0.22	-13.66		24.91	-1.14	-10.41		18.83	1.79	-10.74
	20.38	0.24	-13.68		23.41	-1.52	-10.67		16.83	1.63	-11.48
	18.44	0.57	-13.11		21.62	-1.88	-11.06		14.63	1.56	-12.02
	16.86	1.00	-13.34		20.12	-1.85	-11.80		13.00	1.08	-12.26
	15.03	1.61	-12.85		18.50	-2.32	-12.35		11.07	1.04	-12.09
	13.06	1.58	-12.56		16.89	-2.24	-12.95		8.86	1.04	-12.42
	11.17	1.49	-11.32		15.14	-2.22	-13.35		6.48	1.04	-12.29
	9.76	1.79	-10.21		13.38	-1.99	-13.61		4.79	1.43	-12.26
	7.45	1.75	-8.21		11.45	-1.61	-13.63		2.87	1.87	-12.16
	3.52	-0.21	-9.70		10.05	-0.70	-13.37				
	1.68	-1.04	-12.25		8.94	0.17	-13.00				
					6.76	0.96	-12.56				
					5.19	1.56	-12.36				
					3.64	1.09	-12.09				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M2	22.98	2.16	-7.23	MC M3	28.68	-1.70	-12.02	MC M2	24.36	0.22	-12.12
20160	21.10	1.98	-6.91	20160	26.83	-0.64	-12.55	20165	22.35	0.33	-12.55
	19.57	1.90	-7.27		25.13	-0.68	-12.22		20.52	1.10	-12.29
	17.93	1.25	-8.15		23.59	-0.30	-12.17		18.91	1.90	-12.71
	16.15	0.74	-9.10		21.72	-0.39	-11.61		17.63	1.89	-12.31
	14.46	-0.08	-10.56		19.53	0.30	-11.79		15.53	2.36	-12.09
	12.75	-0.54	-11.71		17.50	-0.01	-11.72		14.10	2.57	-12.12
	11.39	-1.35	-12.72		15.84	0.40	-10.98		12.31	1.87	-11.60
	9.47	-1.62	-13.41		13.77	0.50	-10.81		10.48	1.05	-11.58
	7.63	-1.89	-13.58		11.41	-0.10	-10.66		8.55	1.08	-11.02
	5.89	-1.51	-13.79		9.52	-0.10	-10.65		7.10	0.10	-10.95
	4.25	-1.27	-13.86		7.68	-0.10	-11.00		5.08	-0.59	-11.87
	3.08	-0.22	-12.92		5.75	-1.08	-11.74		3.26	-0.52	-12.29
					4.03	-2.08	-12.09		1.16	0.55	-11.53
					2.40	-2.45	-13.43				
MC M3	30.54	-0.39	-10.98	MC M3	25.79	-0.17	-11.01	MC M3	29.03	-0.29	-9.42
20165	28.53	0.87	-11.40	11132	23.80	-0.41	-11.55	11134	27.16	-0.70	-9.18
	26.63	-0.99	-11.10		22.22	-0.49	-12.11		25.66	-0.96	-9.64
	24.69	-0.04	-10.86		20.59	-0.81	-12.29		23.73	-1.29	-10.78
	22.73	-0.54	-11.47		18.66	-0.18	-12.60		21.77	-1.53	-11.38
	20.75	-1.14	-11.72		17.00	0.08	-12.75		20.07	-1.18	-11.65
	19.02	-1.60	-11.77		14.96	0.56	-12.90		18.33	-0.57	-12.05
	17.19	-1.03	-12.28		13.22	0.88	-12.43		16.73	0.34	-11.95
	15.33	-1.29	-11.77		10.77	1.02	-12.05		14.86	0.48	-12.10
	13.09	-1.36	-11.67		9.27	0.64	-12.11		13.03	0.85	-11.67
	10.43	0.61	-12.21		7.74	0.64	-11.67		8.16	1.11	-11.45
	8.28	0.82	-11.94		5.90	0.30	-11.39		6.20	0.68	-12.34
	6.38	0.51	-11.14		4.45	-0.20	-10.83		4.43	1.24	-10.44
	3.46	0.95	-9.10		3.08	-0.37	-9.95				
	1.70	0.63	-10.57								

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M3 11138	30	1.32	-9.63
	28.12	1.17	-9.51
	25.99	0.75	-9.64
	24.09	0.64	-9.76
	22.46	0.27	-10.06
	20.84	-0.03	-10.39
	19.15	-0.25	-10.71
	17.33	-0.87	-11.47
	15.49	-1.27	-12.31
	13.73	-1.17	-12.59
	11.26	-0.74	-12.57
	9.94	-0.06	-12.25
	7.78	0.65	-12.09
	6.76	1.39	-11.49
	4.93	1.19	-10.78
	4.24	0.99	-10.56
	2.32	0.20	-9.95

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
BTB	31.99	1.41	-10.50	BTB	16.33	-3.02	-11.94	BTB	24.02	-1.54	-9.79
M2	30.50	1.14	-10.76	M2	14.38	-2.39	-11.89	M3	22.16	-2.31	-10.34
3249	29.01	0.51	-10.99	3270	12.59	-1.76	-11.92	3270	20.59	-3.14	-10.70
	27.38	0.21	-10.84		10.95	-0.95	-11.97		18.79	-3.60	-10.17
	25.64	-0.66	-10.82		9.15	-0.38	-11.96		16.88	-3.41	-10.71
	23.62	-1.27	-10.93		7.69	0.53	-11.41		15.07	-2.57	-10.71
	22.00	-2.07	-11.16		6.26	0.37	-11.42		13.47	-2.24	-10.94
	20.66	-2.89	-11.36		4.63	0.81	-10.83		11.96	-1.22	-11.25
	18.79	-3.55	-11.32		2.93	0.85	-10.26		9.85	-0.34	-11.46
	17.49	-4.30	-11.48		1.03	0.03	-9.45		8.04	-0.19	-11.53
	15.26	-4.59	-11.25						4.50	-0.90	-11.59
	13.25	-4.40	-11.23						3.46	-2.07	-11.56
	11.03	-4.08	-11.71								
	9.67	-2.88	-11.87								
	7.29	-1.35	-12.10								
	5.53	-0.32	-11.65								
BTB	32.04	0.63	-11.51	BTB	27.40	0.20	-10.74				
M2	30.46	-0.50	-11.80	M3	25.67	-0.41	-10.76				
3271	28.03	-1.29	-11.52	3031	23.95	-0.14	-10.76				
	26.12	-2.46	-11.79		21.78	-0.44	-10.66				
	23.92	-3.68	-11.97		20.01	-0.71	-10.59				
	22.33	-3.90	-12.18		18.54	-1.21	-10.59				
	20.19	-4.49	-12.33		16.68	-1.77	-11.11				
	18.20	-4.30	-12.38		14.75	-2.51	-11.09				
	16.55	-3.90	-12.47		13.08	-2.88	-11.26				
	14.33	-2.88	-12.12		11.39	-3.44	-11.42				
	12.24	-1.63	-12.35		9.97	-3.54	-11.48				
	10.63	-0.48	-12.26		8.40	-3.10	-11.75				
	8.08	-0.14	-12.23		6.71	-1.98	-11.70				
					5.04	-0.64	-11.84				
					3.06	1.06	-11.56				
					1.69	0.77	-11.45				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2 174	30.10	0.95	-11.19	O M2	30.05	-1.34	-11.62	O M3	31.61	0.14	-10.72
	27.94	0.71	-11.15	205	28.31	-2.10	-11.65	205	30.02	-0.28	-10.33
	26.27	0.04	-11.12		26.81	-2.27	-11.59		28.51	-1.08	-10.60
	24.34	-0.23	-11.37		25.49	-2.26	-11.54		27.08	-1.03	-10.44
	22.63	-1.04	-11.69		24.05	-3.22	-11.68		25.56	-0.64	-10.67
	20.98	-1.96	-11.82		22.44	-3.75	-11.53		24.06	-0.52	-10.94
	19.72	-2.33	-11.97		21.02	-3.76	-11.64		22.46	-0.20	-11.26
	17.81	-2.78	-11.92		19.29	-4.04	-11.79		21.13	0.21	-11.08
	16.18	-2.76	-12.17		17.95	-4.01	-11.96		19.57	0.43	-11.16
	14.55	-3.22	-12.18		15.94	-4.13	-12.33		17.91	0.85	-11.34
	12.86	-2.81	-12.29		14.10	-3.58	-12.34		16.00	1.04	-11.36
	11.42	-2.25	-12.21		12.47	-3.44	-12.31		14.42	1.74	-11.47
	10.04	-1.86	-12.16		10.85	-2.97	-12.28		12.51	2.47	-11.54
	8.83	-1.10	-12.09		9.22	-2.28	-11.94		11.02	2.17	-11.67
	7.23	-0.43	-11.99		7.64	-0.80	-11.61		8.97	1.10	-11.59
	5.49	0.21	-11.99						7.05	0.59	-11.56
	3.87	0.33	-11.84						6.10	-0.23	-11.36
	2.13	0.66	-11.24						4.37	-0.67	-11.64
									2.78	-1.56	-11.95

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2	22.02	-3.05	-10.81	O M3	30.47	-2.39	-10.79	O M2	23.38	-2.61	-12.37
318	20.59	-2.29	-10.94	318	28.89	-2.34	-11.37	348	21.64	-2.50	-12.79
	18.88	-1.66	-11.08		27.07	-2.10	-11.31		20.10	-2.07	-12.27
	17.22	-1.24	-11.22		25.36	-1.47	-11.04		18.44	-2.06	-12.37
	15.90	-0.83	-11.13		24.20	-1.09	-10.88		16.68	-1.76	-11.99
	14.04	-0.22	-11.16		22.33	-0.33	-10.55		15.01	-1.65	-12.09
	12.50	0.31	-11.29		20.81	0.87	-10.64		13.71	-1.37	-11.74
	10.72	0.05	-11.14		19.44	1.22	-10.80		11.70	-1.30	-11.42
	8.83	0.16	-10.71		17.61	1.63	-10.71		10.23	-1.02	-11.03
	6.95	-0.03	-10.51		15.63	1.91	-10.43		8.58	-1.00	-10.87
	5.42	-0.99	-10.82		14.27	1.74	-10.37		6.86	-1.27	-11.35
	3.31	-0.56	-10.48		12.37	1.22	-10.28		4.84	-1.84	-11.30
	1.67	-2.55	-11.00		11.07	0.60	-10.18		3.38	-2.79	-11.18
					9.61	-0.08	-10.51		1.88	-3.22	-11.27
					8.27	-0.82	-10.70		0.26	-3.88	-11.42
					7.01	-1.57	-11.20				
					5.81	-2.19	-11.38				
O M2	29.96	-1.48	-10.46		4.03	-2.40	-11.28	O M3	28.08	1.28	-11.36
478	27.61	-2.15	-11.46		3.16	-1.84	-11.07	478	26.21	1.34	-10.76
	25.41	-2.71	-11.66		0.52	-1.71	-11.16		24.36	1.38	-10.43
	23.79	-2.95	-11.84						20.97	2.06	-10.14
	21.78	-2.58	-11.50						19.44	1.94	-10.00
	20.31	-2.08	-11.31						18.04	1.61	-9.78
	18.45	-1.50	-11.00						16.34	1.11	-9.86
	16.52	-1.14	-10.97						14.67	0.20	-9.86
	14.41	0.24	-10.79						12.95	-0.24	-10.13
	12.92	0.85	-10.27						11.61	-0.96	-10.52
	11.29	0.83	-10.23						9.62	-1.75	-11.33
	9.64	0.82	-10.30						7.78	-3.04	-11.57
	8.18	0.90	-10.06						6.04	-3.10	-11.52
	6.66	0.81	-9.70						4.30	-2.00	-10.75
	4.75	-0.07	-9.84								
	2.92	0.17	-10.57								

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2 482	29.92	-0.72	-12.91	O M2	27.88	-1.26	-11.00
	28.07	-1.68	-12.97	484	26.19	-1.52	-11.06
	26.07	-2.54	-13.09		24.54	-2.10	-11.04
	24.20	-2.87	-13.28		23.04	-2.59	-10.88
	21.69	-3.20	-13.27		21.08	-2.97	-10.94
	20.00	-3.09	-13.32		19.56	-3.46	-11.40
	18.52	-2.91	-13.33		17.91	-3.50	-11.48
	16.79	-2.44	-13.12		16.04	-3.62	-11.59
	15.20	-1.63	-12.97		14.16	-2.82	-11.43
	13.40	-0.96	-12.86		12.38	-2.79	-11.79
	11.57	-0.10	-12.98		10.31	-2.17	-11.51
	9.86	0.82	-12.82		8.52	-1.23	-11.85
	8.09	0.81	-12.98		6.42	-1.41	-11.76
	5.86	0.05	-12.73		4.53	-0.73	-12.59
	4.30	0.46	-12.66				
	3.13	-0.06	-12.29				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
TR M2 725	27.79	0.66	-9.24	TR M3 725	33.17	1.89	-8.45	TR M2 763	28.69	2.18	-9.72
	26.70	0.27	-9.76		31.27	1.44	-8.31		26.92	1.37	-10.27
	24.98	0.07	-10.51		29.63	1.43	-8.47		25.25	1.05	-10.80
	23.12	0.01	-11.19		28.24	1.16	-9.09		23.92	0.79	-11.43
	21.29	-0.30	-11.42		26.53	0.93	-9.33		22.10	0.05	-12.04
	19.73	-0.19	-11.69		24.95	0.82	-10.13		20.46	-0.39	-12.43
	18.33	-0.25	-11.72		23.03	0.15	-10.88		18.53	-0.44	-12.59
	16.67	-0.35	-11.65		21.71	0.01	-11.87		16.81	-0.29	-12.48
	15.11	-0.05	-11.58		19.88	-0.09	-12.10		14.89	0.31	-12.30
	13.72	0.53	-11.38		18.11	-0.01	-12.44		13.36	0.94	-12.20
	12.30	1.06	-10.95		16.07	0.11	-12.51		11.89	1.07	-11.81
	10.32	1.63	-10.07		14.07	0.62	-11.83		9.93	1.90	-11.76
	8.73	1.88	-9.94		12.51	0.72	-11.33		8.35	1.90	-11.24
	7.33	1.73	-9.35		10.49	1.31	-11.15		6.66	1.85	-10.79
	5.20	1.50	-9.43		8.76	1.30	-10.62		5.05	1.40	-10.95
	3.93	1.87	-8.91		6.96	1.07	-9.80		3	0.80	-11.46
	2.59	0.50	-9.65						1.85	0.28	-12.71
	1.38	0.73	-10.32								
TR M3 763	28.81	2.08	-11.66	TR M2 831	30.30	0.96	-7.57	TR M3 831	30.55	1.44	-11.45
	27.15	2.44	-11.31		28.54	0.56	-7.81		29.03	1.24	-11.55
	25.77	2.59	-10.89		26.79	0.10	-9.06		27.24	1.16	-11.46
	24.26	1.94	-10.70		25.11	0.16	-9.58		25.42	1.25	-10.82
	22.84	2.23	-10.26		23.23	0.31	-10.63		23.76	1.03	-10.44
	21.46	1.81	-10.48		21.61	0.11	-11.69		22.19	0.82	-9.96
	19.75	1.68	-10.27		19.94	0.70	-12.64		20.63	0.98	-9.57
	16.63	1.23	-10.81		18.14	0.77	-12.93		18.75	0.61	-9.30
	15.33	0.93	-11.64		16.63	1.17	-13.21		17.28	0.22	-9.07
	13.49	0.46	-12.39		15.15	1.90	-12.74		15.47	0.13	-9.05
	11.75	0.47	-13.21		13.58	2.14	-12.44		13.10	-0.20	-10.07
	10.10	0.57	-12.99		12.09	2.37	-12.24		11.45	-0.51	-11.47
	8.06	0.57	-12.94		10.61	1.38	-11.59		9.06	-0.96	-12.53
	6.38	0.14	-12.79		8.57	1.08	-11.40				
	3.77	0.64	-12.79		7.47	0.92	-10.95				
					5.85	0.56	-10.44				
					3.77	0.12	-9.63				

Beyond the herd: investigating livestock feeding strategies in the Iron Age Iberian Peninsula (3rd c. BC) through a multi-isotope analysis
Chiara Messina*; **Carlos Tornado***; **Lidia Colominas**
*** Corresponding authors**

Institut Català de Paleoeologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain (ES)

Universitat Rovira i Virgili (URV), Departament d'Història i Història de l'Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain (ES)

Department of Prehistory, Autonomous University of Barcelona (UAB), Edifici B, Facultat de Filosofia i Lletres, 08193 Bellaterra, Spain (ES)

cmessana@iphes.cat

Carlos.Tornado@uab.cat

Supplementary Table 1. $\delta^{18}\text{O}_{\text{V-PDB}}$ and $\delta^{13}\text{C}_{\text{V-PDB}}$ values measured on enamel bioapatite of sheep lower second (M_2) and third (M_3) molars.

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M2	30.84	-0.89	-10.06	MC M2	33.25	1.57	-10.62	MC M2	26.86	2.10	-7.45
11144	29.09	-1.05	-10.66	12023	31.76	0.88	-10.04	20102	25.08	1.92	-8.16
	27.28	-1.04	-12.09		30.00	0.59	-9.85		23.44	1.89	-8.30
	25.57	-1.00	-12.56		28.67	-0.19	-9.85		21.93	1.87	-9.34
	24.02	-0.62	-13.27		27.18	-0.51	-9.92		20.23	1.70	-10.15
	22.02	-0.22	-13.66		24.91	-1.14	-10.41		18.83	1.79	-10.74
	20.38	0.24	-13.68		23.41	-1.52	-10.67		16.83	1.63	-11.48
	18.44	0.57	-13.11		21.62	-1.88	-11.06		14.63	1.56	-12.02
	16.86	1.00	-13.34		20.12	-1.85	-11.80		13.00	1.08	-12.26
	15.03	1.61	-12.85		18.50	-2.32	-12.35		11.07	1.04	-12.09
	13.06	1.58	-12.56		16.89	-2.24	-12.95		8.86	1.04	-12.42
	11.17	1.49	-11.32		15.14	-2.22	-13.35		6.48	1.04	-12.29
	9.76	1.79	-10.21		13.38	-1.99	-13.61		4.79	1.43	-12.26
	7.45	1.75	-8.21		11.45	-1.61	-13.63		2.87	1.87	-12.16
	3.52	-0.21	-9.70		10.05	-0.70	-13.37				
	1.68	-1.04	-12.25		8.94	0.17	-13.00				
					6.76	0.96	-12.56				
					5.19	1.56	-12.36				
					3.64	1.09	-12.09				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M2	22.98	2.16	-7.23	MC M3	28.68	-1.70	-12.02	MC M2	24.36	0.22	-12.12
20160	21.10	1.98	-6.91	20160	26.83	-0.64	-12.55	20165	22.35	0.33	-12.55
	19.57	1.90	-7.27		25.13	-0.68	-12.22		20.52	1.10	-12.29
	17.93	1.25	-8.15		23.59	-0.30	-12.17		18.91	1.90	-12.71
	16.15	0.74	-9.10		21.72	-0.39	-11.61		17.63	1.89	-12.31
	14.46	-0.08	-10.56		19.53	0.30	-11.79		15.53	2.36	-12.09
	12.75	-0.54	-11.71		17.50	-0.01	-11.72		14.10	2.57	-12.12
	11.39	-1.35	-12.72		15.84	0.40	-10.98		12.31	1.87	-11.60
	9.47	-1.62	-13.41		13.77	0.50	-10.81		10.48	1.05	-11.58
	7.63	-1.89	-13.58		11.41	-0.10	-10.66		8.55	1.08	-11.02
	5.89	-1.51	-13.79		9.52	-0.10	-10.65		7.10	0.10	-10.95
	4.25	-1.27	-13.86		7.68	-0.10	-11.00		5.08	-0.59	-11.87
	3.08	-0.22	-12.92		5.75	-1.08	-11.74		3.26	-0.52	-12.29
					4.03	-2.08	-12.09		1.16	0.55	-11.53
					2.40	-2.45	-13.43				
MC M3	30.54	-0.39	-10.98	MC M3	25.79	-0.17	-11.01	MC M3	29.03	-0.29	-9.42
20165	28.53	0.87	-11.40	11132	23.80	-0.41	-11.55	11134	27.16	-0.70	-9.18
	26.63	-0.99	-11.10		22.22	-0.49	-12.11		25.66	-0.96	-9.64
	24.69	-0.04	-10.86		20.59	-0.81	-12.29		23.73	-1.29	-10.78
	22.73	-0.54	-11.47		18.66	-0.18	-12.60		21.77	-1.53	-11.38
	20.75	-1.14	-11.72		17.00	0.08	-12.75		20.07	-1.18	-11.65
	19.02	-1.60	-11.77		14.96	0.56	-12.90		18.33	-0.57	-12.05
	17.19	-1.03	-12.28		13.22	0.88	-12.43		16.73	0.34	-11.95
	15.33	-1.29	-11.77		10.77	1.02	-12.05		14.86	0.48	-12.10
	13.09	-1.36	-11.67		9.27	0.64	-12.11		13.03	0.85	-11.67
	10.43	0.61	-12.21		7.74	0.64	-11.67		8.16	1.11	-11.45
	8.28	0.82	-11.94		5.90	0.30	-11.39		6.20	0.68	-12.34
	6.38	0.51	-11.14		4.45	-0.20	-10.83		4.43	1.24	-10.44
	3.46	0.95	-9.10		3.08	-0.37	-9.95				
	1.70	0.63	-10.57								

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
MC M3 11138	30	1.32	-9.63
	28.12	1.17	-9.51
	25.99	0.75	-9.64
	24.09	0.64	-9.76
	22.46	0.27	-10.06
	20.84	-0.03	-10.39
	19.15	-0.25	-10.71
	17.33	-0.87	-11.47
	15.49	-1.27	-12.31
	13.73	-1.17	-12.59
	11.26	-0.74	-12.57
	9.94	-0.06	-12.25
	7.78	0.65	-12.09
	6.76	1.39	-11.49
	4.93	1.19	-10.78
	4.24	0.99	-10.56
	2.32	0.20	-9.95

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
BTB	31.99	1.41	-10.50	BTB	16.33	-3.02	-11.94	BTB	24.02	-1.54	-9.79
M2	30.50	1.14	-10.76	M2	14.38	-2.39	-11.89	M3	22.16	-2.31	-10.34
3249	29.01	0.51	-10.99	3270	12.59	-1.76	-11.92	3270	20.59	-3.14	-10.70
	27.38	0.21	-10.84		10.95	-0.95	-11.97		18.79	-3.60	-10.17
	25.64	-0.66	-10.82		9.15	-0.38	-11.96		16.88	-3.41	-10.71
	23.62	-1.27	-10.93		7.69	0.53	-11.41		15.07	-2.57	-10.71
	22.00	-2.07	-11.16		6.26	0.37	-11.42		13.47	-2.24	-10.94
	20.66	-2.89	-11.36		4.63	0.81	-10.83		11.96	-1.22	-11.25
	18.79	-3.55	-11.32		2.93	0.85	-10.26		9.85	-0.34	-11.46
	17.49	-4.30	-11.48		1.03	0.03	-9.45		8.04	-0.19	-11.53
	15.26	-4.59	-11.25						4.50	-0.90	-11.59
	13.25	-4.40	-11.23						3.46	-2.07	-11.56
	11.03	-4.08	-11.71								
	9.67	-2.88	-11.87								
	7.29	-1.35	-12.10								
	5.53	-0.32	-11.65								
BTB	32.04	0.63	-11.51	BTB	27.40	0.20	-10.74				
M2	30.46	-0.50	-11.80	M3	25.67	-0.41	-10.76				
3271	28.03	-1.29	-11.52	3031	23.95	-0.14	-10.76				
	26.12	-2.46	-11.79		21.78	-0.44	-10.66				
	23.92	-3.68	-11.97		20.01	-0.71	-10.59				
	22.33	-3.90	-12.18		18.54	-1.21	-10.59				
	20.19	-4.49	-12.33		16.68	-1.77	-11.11				
	18.20	-4.30	-12.38		14.75	-2.51	-11.09				
	16.55	-3.90	-12.47		13.08	-2.88	-11.26				
	14.33	-2.88	-12.12		11.39	-3.44	-11.42				
	12.24	-1.63	-12.35		9.97	-3.54	-11.48				
	10.63	-0.48	-12.26		8.40	-3.10	-11.75				
	8.08	-0.14	-12.23		6.71	-1.98	-11.70				
					5.04	-0.64	-11.84				
					3.06	1.06	-11.56				
					1.69	0.77	-11.45				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2 174	30.10	0.95	-11.19	O M2	30.05	-1.34	-11.62	O M3	31.61	0.14	-10.72
	27.94	0.71	-11.15	205	28.31	-2.10	-11.65	205	30.02	-0.28	-10.33
	26.27	0.04	-11.12		26.81	-2.27	-11.59		28.51	-1.08	-10.60
	24.34	-0.23	-11.37		25.49	-2.26	-11.54		27.08	-1.03	-10.44
	22.63	-1.04	-11.69		24.05	-3.22	-11.68		25.56	-0.64	-10.67
	20.98	-1.96	-11.82		22.44	-3.75	-11.53		24.06	-0.52	-10.94
	19.72	-2.33	-11.97		21.02	-3.76	-11.64		22.46	-0.20	-11.26
	17.81	-2.78	-11.92		19.29	-4.04	-11.79		21.13	0.21	-11.08
	16.18	-2.76	-12.17		17.95	-4.01	-11.96		19.57	0.43	-11.16
	14.55	-3.22	-12.18		15.94	-4.13	-12.33		17.91	0.85	-11.34
	12.86	-2.81	-12.29		14.10	-3.58	-12.34		16.00	1.04	-11.36
	11.42	-2.25	-12.21		12.47	-3.44	-12.31		14.42	1.74	-11.47
	10.04	-1.86	-12.16		10.85	-2.97	-12.28		12.51	2.47	-11.54
	8.83	-1.10	-12.09		9.22	-2.28	-11.94		11.02	2.17	-11.67
	7.23	-0.43	-11.99		7.64	-0.80	-11.61		8.97	1.10	-11.59
	5.49	0.21	-11.99						7.05	0.59	-11.56
	3.87	0.33	-11.84						6.10	-0.23	-11.36
	2.13	0.66	-11.24						4.37	-0.67	-11.64
									2.78	-1.56	-11.95

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2	22.02	-3.05	-10.81	O M3	30.47	-2.39	-10.79	O M2	23.38	-2.61	-12.37
318	20.59	-2.29	-10.94	318	28.89	-2.34	-11.37	348	21.64	-2.50	-12.79
	18.88	-1.66	-11.08		27.07	-2.10	-11.31		20.10	-2.07	-12.27
	17.22	-1.24	-11.22		25.36	-1.47	-11.04		18.44	-2.06	-12.37
	15.90	-0.83	-11.13		24.20	-1.09	-10.88		16.68	-1.76	-11.99
	14.04	-0.22	-11.16		22.33	-0.33	-10.55		15.01	-1.65	-12.09
	12.50	0.31	-11.29		20.81	0.87	-10.64		13.71	-1.37	-11.74
	10.72	0.05	-11.14		19.44	1.22	-10.80		11.70	-1.30	-11.42
	8.83	0.16	-10.71		17.61	1.63	-10.71		10.23	-1.02	-11.03
	6.95	-0.03	-10.51		15.63	1.91	-10.43		8.58	-1.00	-10.87
	5.42	-0.99	-10.82		14.27	1.74	-10.37		6.86	-1.27	-11.35
	3.31	-0.56	-10.48		12.37	1.22	-10.28		4.84	-1.84	-11.30
	1.67	-2.55	-11.00		11.07	0.60	-10.18		3.38	-2.79	-11.18
					9.61	-0.08	-10.51		1.88	-3.22	-11.27
					8.27	-0.82	-10.70		0.26	-3.88	-11.42
					7.01	-1.57	-11.20				
					5.81	-2.19	-11.38				
O M2	29.96	-1.48	-10.46		4.03	-2.40	-11.28	O M3	28.08	1.28	-11.36
478	27.61	-2.15	-11.46		3.16	-1.84	-11.07	478	26.21	1.34	-10.76
	25.41	-2.71	-11.66		0.52	-1.71	-11.16		24.36	1.38	-10.43
	23.79	-2.95	-11.84						20.97	2.06	-10.14
	21.78	-2.58	-11.50						19.44	1.94	-10.00
	20.31	-2.08	-11.31						18.04	1.61	-9.78
	18.45	-1.50	-11.00						16.34	1.11	-9.86
	16.52	-1.14	-10.97						14.67	0.20	-9.86
	14.41	0.24	-10.79						12.95	-0.24	-10.13
	12.92	0.85	-10.27						11.61	-0.96	-10.52
	11.29	0.83	-10.23						9.62	-1.75	-11.33
	9.64	0.82	-10.30						7.78	-3.04	-11.57
	8.18	0.90	-10.06						6.04	-3.10	-11.52
	6.66	0.81	-9.70						4.30	-2.00	-10.75
	4.75	-0.07	-9.84								
	2.92	0.17	-10.57								

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
O M2 482	29.92	-0.72	-12.91	O M2	27.88	-1.26	-11.00
	28.07	-1.68	-12.97	484	26.19	-1.52	-11.06
	26.07	-2.54	-13.09		24.54	-2.10	-11.04
	24.20	-2.87	-13.28		23.04	-2.59	-10.88
	21.69	-3.20	-13.27		21.08	-2.97	-10.94
	20.00	-3.09	-13.32		19.56	-3.46	-11.40
	18.52	-2.91	-13.33		17.91	-3.50	-11.48
	16.79	-2.44	-13.12		16.04	-3.62	-11.59
	15.20	-1.63	-12.97		14.16	-2.82	-11.43
	13.40	-0.96	-12.86		12.38	-2.79	-11.79
	11.57	-0.10	-12.98		10.31	-2.17	-11.51
	9.86	0.82	-12.82		8.52	-1.23	-11.85
	8.09	0.81	-12.98		6.42	-1.41	-11.76
	5.86	0.05	-12.73		4.53	-0.73	-12.59
	4.30	0.46	-12.66				
	3.13	-0.06	-12.29				

Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$	Sample	Dist. from ERJ (mm)	$\delta^{18}\text{O}_{\text{V-PDB}}\text{‰}$	$\delta^{13}\text{C}_{\text{V-PDB}}\text{‰}$
TR M2 725	27.79	0.66	-9.24	TR M3	33.17	1.89	-8.45	TR M2	28.69	2.18	-9.72
	26.70	0.27	-9.76	725	31.27	1.44	-8.31	763	26.92	1.37	-10.27
	24.98	0.07	-10.51		29.63	1.43	-8.47		25.25	1.05	-10.80
	23.12	0.01	-11.19		28.24	1.16	-9.09		23.92	0.79	-11.43
	21.29	-0.30	-11.42		26.53	0.93	-9.33		22.10	0.05	-12.04
	19.73	-0.19	-11.69		24.95	0.82	-10.13		20.46	-0.39	-12.43
	18.33	-0.25	-11.72		23.03	0.15	-10.88		18.53	-0.44	-12.59
	16.67	-0.35	-11.65		21.71	0.01	-11.87		16.81	-0.29	-12.48
	15.11	-0.05	-11.58		19.88	-0.09	-12.10		14.89	0.31	-12.30
	13.72	0.53	-11.38		18.11	-0.01	-12.44		13.36	0.94	-12.20
	12.30	1.06	-10.95		16.07	0.11	-12.51		11.89	1.07	-11.81
	10.32	1.63	-10.07		14.07	0.62	-11.83		9.93	1.90	-11.76
	8.73	1.88	-9.94		12.51	0.72	-11.33		8.35	1.90	-11.24
	7.33	1.73	-9.35		10.49	1.31	-11.15		6.66	1.85	-10.79
	5.20	1.50	-9.43		8.76	1.30	-10.62		5.05	1.40	-10.95
	3.93	1.87	-8.91		6.96	1.07	-9.80		3	0.80	-11.46
TR M3 763	2.59	0.50	-9.65	TR M2 831	30.30	0.96	-7.57	TR M3 831	1.85	0.28	-12.71
	1.38	0.73	-10.32			0.56	-7.81		30.55	1.44	-11.45
	28.81	2.08	-11.66			28.54	-7.81		29.03	1.24	-11.55
	27.15	2.44	-11.31			26.79	-9.06		27.24	1.16	-11.46
	25.77	2.59	-10.89			25.11	-9.58		25.42	1.25	-10.82
	24.26	1.94	-10.70			23.23	-10.63		23.76	1.03	-10.44
	22.84	2.23	-10.26			21.61	-11.69		22.19	0.82	-9.96
	21.46	1.81	-10.48			19.94	-12.64		20.63	0.98	-9.57
	19.75	1.68	-10.27			18.14	-12.93		18.75	0.61	-9.30
	16.63	1.23	-10.81			16.63	-13.21		17.28	0.22	-9.07
	15.33	0.93	-11.64			15.15	-12.74		15.47	0.13	-9.05
	13.49	0.46	-12.39			13.58	-12.44		13.10	-0.20	-10.07
	11.75	0.47	-13.21			12.09	-12.24		11.45	-0.51	-11.47
	10.10	0.57	-12.99			10.61	-11.59		9.06	-0.96	-12.53
	8.06	0.57	-12.94			8.57	-11.40				
	6.38	0.14	-12.79			7.47	-10.95				
	3.77	0.64	-12.79			5.85	-10.44				

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TALES OF SHEEP IN THE NORTH-EASTERN IBERIAN PENINSULA DURING THE IRON AGE (3RD CENTURY BC) : A MULTI-ISOTOPE RESEARCH

Chiara Messina



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