



**HAL**  
open science

## Carefully sourced, carefully managed: multi-isotopic analysis from Bronze and Iron Age equid teeth from Can Roqueta (Barcelona, Spain)

S. Valenzuela-Lamas, M. Díaz-Zorita Bonilla, S. Albizuri, L.D. Pena, Delphine Bosch, M.E. Subirà, F.J. López-Cachero

### ► To cite this version:

S. Valenzuela-Lamas, M. Díaz-Zorita Bonilla, S. Albizuri, L.D. Pena, Delphine Bosch, et al.. Carefully sourced, carefully managed: multi-isotopic analysis from Bronze and Iron Age equid teeth from Can Roqueta (Barcelona, Spain). *Journal of Archaeological Science: Reports*, 2023, 49, pp.104032. 10.1016/j.jasrep.2023.104032 . hal-04236418

**HAL Id: hal-04236418**

<https://hal.science/hal-04236418v1>

Submitted on 12 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License



## Carefully sourced, carefully managed: multi-isotopic analysis from Bronze and Iron Age equid teeth from Can Roqueta (Barcelona, Spain)

S. Valenzuela-Lamas<sup>a,\*</sup>, M. Díaz-Zorita Bonilla<sup>b</sup>, S. Albizuri<sup>c</sup>, L.D. Pena<sup>d</sup>, D. Bosch<sup>e</sup>, M.E. Subirà<sup>f</sup>, F.J. López-Cachero<sup>c</sup>

<sup>a</sup> *Archaeology of Social Dynamics, Institució Milà i Fontanals, Consejo Superior de Investigaciones Científicas (IMF-CSIC), Spain*

<sup>b</sup> *Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, University of Tübingen, Germany*

<sup>c</sup> *Institut d'Arqueologia de la Universitat de Barcelona (IAUB). Seminari d'Estudis i Recerques Prehistòriques (SERP-UB), Universitat de Barcelona (UB), Spain*

<sup>d</sup> *GRC Geociències Marines, Departament de Dinàmica de la Terra i de l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona, c/ Martí i Franquès s/n, 08028 Barcelona, Spain*

<sup>e</sup> *Géosciences Montpellier, Université de Montpellier - CNRS, UMR 5243, Pl. Eugène Bataillon, 34090 Montpellier, France*

<sup>f</sup> *GREAB (Grup de Recerca en Antropologia Biològica, SGR2017 1630), Unitat d'Antropologia Biològica, Universitat Autònoma de Barcelona (UAB), Spain*

### ARTICLE INFO

#### Keywords:

Equus  
Strontium  
Oxygen  
Carbon  
Isotopes  
Iberia  
Mobility  
Herding

### ABSTRACT

Equids played an important role in the development of communication in past societies, and were part of the exchanges between populations. The multi-isotopic study (strontium, carbon and oxygen isotopes) conducted on equid teeth from Bronze and Early Iron Age Can Roqueta suggests that animals originate from diverse locations and their diet was carefully managed. The enriched oxygen and carbon isotopic ratios in equid teeth compared with other taxa from the same site suggest that equids may have drunk from water troughs, thus creating a <sup>13</sup>C and <sup>18</sup>O isotopic enrichment and partial covariance, similar to a “lake” effect. This is the most comprehensive study on equid mobility in Iberia so far.

### 1. Introduction

Equids have played a fundamental role in labour, communication and warfare since their domestication in Central Asia and later in the Western Eurasian steppe (Librado et al. 2021), and they also have a strong symbolic value (e.g. Dolce 2014). Equid taming and breeding – specially in horses – is known to require higher time investment and precise knowledge compared to other domesticates (e.g. Varro II, VII, 16). Consequently, some researchers have hypothesised that some Late rehistoric sites in Europe may have specialised in horse breeding and supplied other sites with these valuable animals (e.g. Harcourt, 1979; Grant, 1984; Bendrey et al., 2009; Bendrey, 2010).

Equid remains are frequently found in the zooarchaeological assemblages in NE Iberia from the 12th c. BCE onwards, and their presence notably increased from the Early Iron Age (8th-6th c. BCE; e.g. Albizuri et al., 2011; Nieto-Espinet 2012; Albizuri, 2014). So far, two sites in NE Iberia –Vilars d'Arbeca and Tossal del Molinet– strongly suggest the presence of local equid breeding, as evidenced by the recovered equid foetal remains (e.g. Gómez, 2003; Nieto-Espinet et al., 2010; Nieto-

Espinet 2012). The absence of foetal and juvenile equid remains at other synchronic sites raises the question whether some settlements specialised in equid breeding or rather it was a wide-spread practice that let very few traces in the archaeological record.

The present work expands previous research on the geographical origin of the equids registered at Can Roqueta during Late Prehistory (Late Bronze Age to Middle Iron Age; Albizuri et al. 2019). A total of 21 animals have been added to the 6 equids previously analysed for <sup>87</sup>Sr/<sup>86</sup>Sr isotopic ratios, and it is possible now to present multi-isotopic data (strontium, <sup>87</sup>Sr/<sup>86</sup>Sr, oxygen δ<sup>18</sup>O and carbon δ<sup>13</sup>C isotopic ratios) from 22 equids dated from the Late Bronze Age and the Early Iron Age along with a dog, a pig and three rabbits. In addition, targeted sequential sampling of enamel carbonate for both oxygen (δ<sup>18</sup>O) and carbon (δ<sup>13</sup>C) isotopic ratios allow us to provide the first results of seasonal oxygen and carbon isotopic variation in equid remains in NE Iberia. This provides a better image of the variability and range of equid breeding and sourcing at Can Roqueta, together with valuable information to contribute to the debate about equid sourcing and management during Late Prehistory in this area. This paper constitutes the most comprehensive study on this

\* Corresponding author.

E-mail address: [svalenzuela@imf.csic.es](mailto:svalenzuela@imf.csic.es) (S. Valenzuela-Lamas).

<https://doi.org/10.1016/j.jasrep.2023.104032>

Received 29 July 2022; Received in revised form 28 April 2023; Accepted 28 April 2023

Available online 29 May 2023

2352-409X/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

topic in Iberia so far.

## 2. Materials and methods

### 2.1. The site of Can Roqueta (Sabadell, Barcelona)

The extensive archaeological complex of Can Roqueta is located in the pre-coastal zone of Barcelona (Sabadell, Vallès Occidental) (Fig. 1). The site preserved numerous structures among which 120 excavated silos (Palomo et al. 2016) spanning a broad chronological sequence ranging from the Neolithic to the Late Roman period. The best

represented periods are the Early/Middle Bronze Age (E-MBA) (2300–1300 cal. BCE), the Late Bronze Age (LBA) (1300–750 cal. BCE) and the Early Iron Age (EIA) (750–550 cal. BCE; Carlús et al., 2007).

The study of the archaeobotanical and archaeozoological remains dated from the Late Bronze Age (LBA) and the Early Iron Age (EIA) suggest that the inhabitants of Can Roqueta focused on cultivating cereals and legumes (Antolín 2008) complemented by raising livestock for meat, milk, and traction (Casellas et al. 1999, Piña and Saña 2004, Albizuri 2008). Faunal remains reveal a livestock farming model based on the rearing of sheep and goats (*Ovis/Capra*) for meat and milk, followed by pigs (*Sus domesticus*). Cattle (*Bos taurus*) were mainly used for

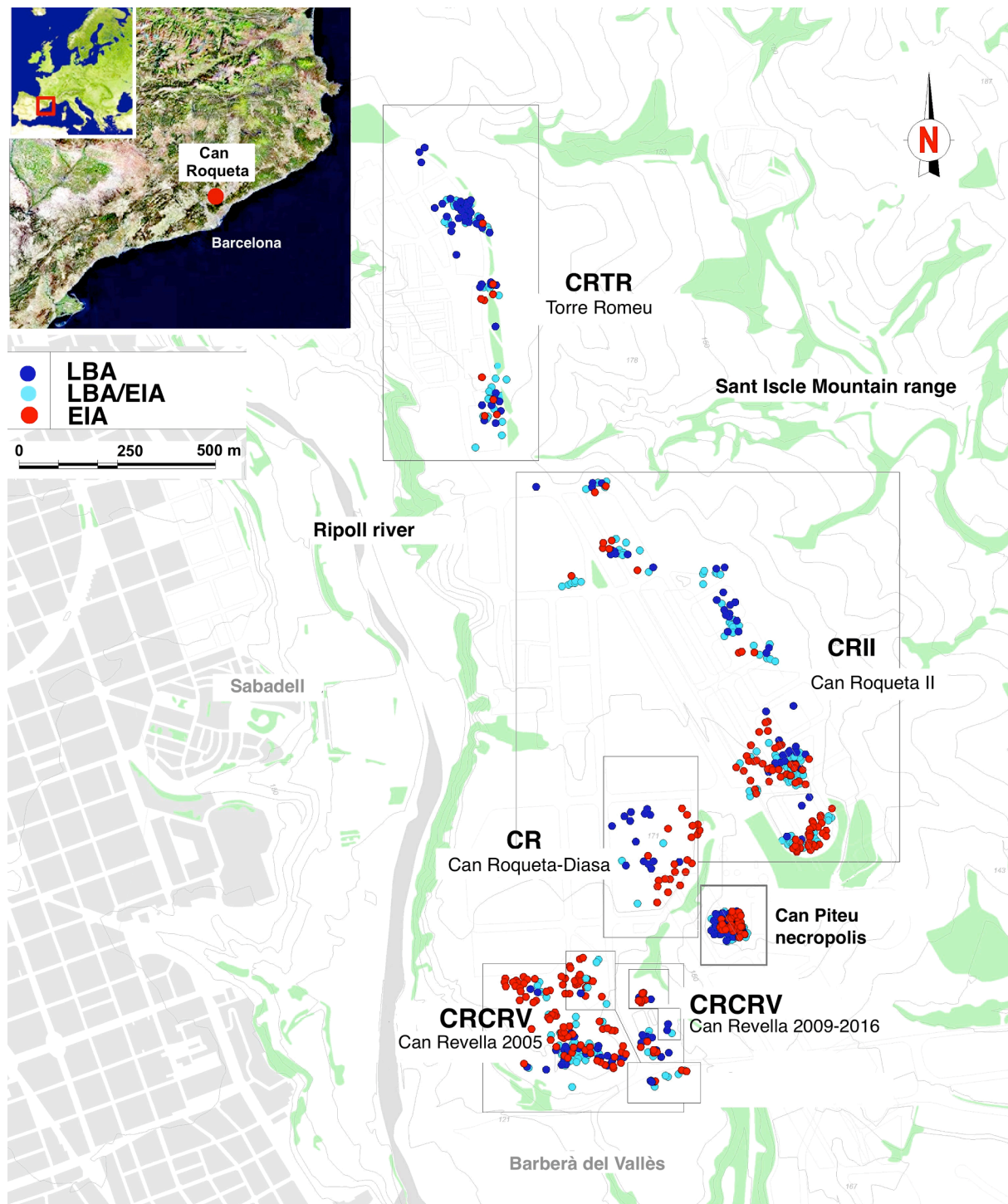


Fig. 1. Location and plan of the different sectors of Can Roqueta (Sabadell, Spain).

agricultural work but they were also slaughtered for meat at the end of their working life (see citations above). The first records of horse bones (*Equus caballus*) appear in the LBA (Albizuri et al. 2021). Eighteen horses have been identified according to the minimum number of animals (MNI = 18; NISP = 37). In the EIA, there was a very significant increase of equid presence and forty-six individuals (MNI) were recorded, represented by 381 remains (NISP counts do not include the complete specimens CR6 and CRII811; Albizuri et al. 2021).

All the analysed equids come from negative structures excavated in the subsoil with no stratigraphic relationship between them. In many cases their chronology was assessed based on the associated material culture, which allowed us to clearly differentiate three main periods: the Late Bronze Age (LBA), the Early Iron Age (EIA) and the Middle Iron Age (MIA). Seventeen equids were radiocarbon dated to have a better chronological accuracy. Two of them corresponded to LBA, 13 were dated to the EIA, and two equids dated from the Middle Iron Age (MIA,

also known as Iberian Period in the local periodisation).

Fig. 2 shows the calibrated and modelled probability sums of all the radiocarbon dates (OxCal v.4.4.4, Bronk Ramsey, 2023). All the equids in Can Roqueta were deposited between the mid-9th century cal. BCE and the beginning of the 4th century cal. BCE. The two LBA dates coincide in the 9th century cal. BCE (last quarter of the 9th century cal. BCE at one sigma). The EIA dates are difficult to analyse as they systematically fall within the “Hallstatt plateau” with an extensive time frame that occupies the 8th, 7th and 6th centuries cal. BCE (from 790 to 650 BCE). Finally, the two radiocarbon dates from the MIA suggest that these equids were deposited in the 5th century cal. BCE (about 450–400 BCE to one sigma).

To better understand the diachronic sequence of the radiocarbon dates we elaborated a Bayesian model of sequenced phases that we structured in the three periods mentioned (LBA, EIA, MIA). This model presents correlation indices (agreement indices) clearly above 60%

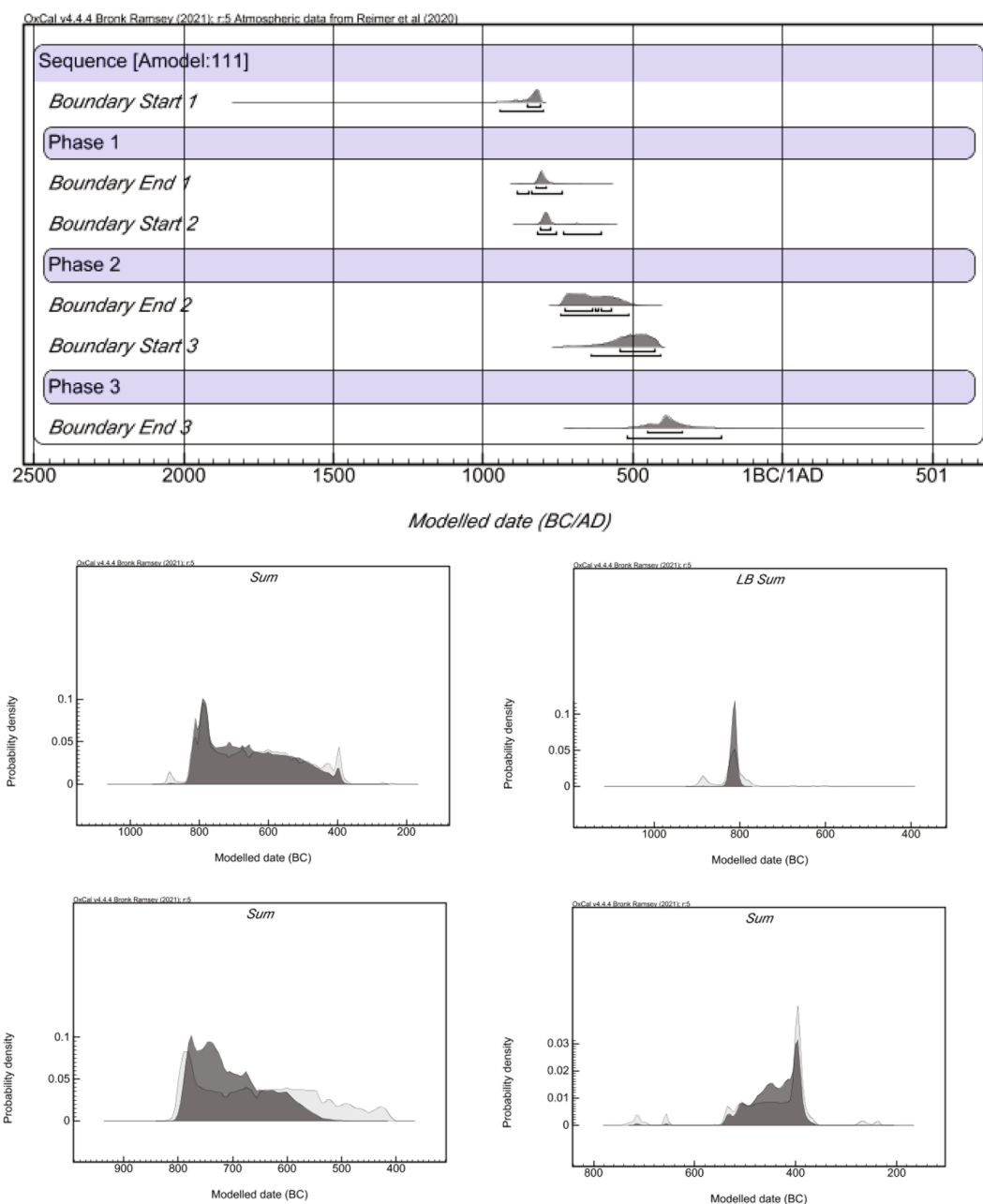


Fig. 2. Limits of the periods considered (A) and sum of calibrated (grey) and modelled (black) Probabilities of the total radiocarbon dates (B), from LBA (C), EIA (D) and MIA (E) (OxCal v.4.4.4 © Bronk Ramsey 2023; r:5 IntCal20. Atmospheric data from Reimer et al. 2020).

( $A_{\text{model}} = 110.1 / A_{\text{overall}} = 91.8$ ) which suggests that it is statistically coherent and supports the distribution of the dates in three chronological phases (see also [supplementary table S1](#) and [supplementary figure S2](#)).

Previous studies on the equid remains from Can Roqueta ([Albizuri et al. 2019](#)) highlighted the absence of young and infant animals buried within the excavated structures, as well as the high presence of equid bones in intentional deposits. Animals were probably sacrificed in ceremonial acts and safely deposited in underground structures in which dogs are also abundant, usually in anatomical connection, together with other domestic species ([López Cachero et al., in press](#)). The absence of young and infant equids suggested a possible foreign origin and specialised equid breeding in certain centres that would distribute these animals once they had been trained ([Albizuri et al. 2019](#)). Zooarchaeological analyses suggest that horses predominated among the equids deposited, although some hybrids and donkeys have also been identified during the EIA, mostly males over 5 years old. This focus on male adults in Iron Age sacrificial deposits has been also attested from EBA assemblages in Eurasia ([Fages et al. 2020](#)) and Iron Age France ([Clavel et al. 2022](#)). The study of the pathologies shows that the equids deposited at Can Roqueta were working and riding animals ([Albizuri et al. 2019](#)). A pilot study based on strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) to assess the geographical provenance of the equids indicated that some individuals were not raised within the site ([Albizuri et al. 2019](#)). The study of their diet through carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotopes showed a high diversity between individuals, thus suggesting that the equid remains deposited at Can Roqueta originate from various farms ([Albizuri et al. 2021](#)). This is consistent with the settlement pattern observed in this area, in which dispersed and culturally homogeneous farms have a shared territory and a great cremation necropolis (Can Piteu-Roqueta; [Carlús et al. 2007](#)).

## 2.2. Oxygen isotopic ratios ( $\delta^{18}\text{O}$ ) in equid tooth enamel carbonates

The oxygen isotope ratios ( $\delta^{18}\text{O}$ ) in tooth bioapatite are known to reflect the oxygen isotopic composition of body water which, in turn, is sourced from atmospheric oxygen, organic compounds in food, and ingested water (e.g. [Luz et al., 1984](#), [Bryant and Froelich 1995](#)). The isotopic composition of water is influenced by a number of factors – e.g. temperature, amount and timing of precipitation; see e.g. [Gat, 1980](#); [Rozanski et al., 1993](#); [Gat, 1996](#); [Kohn and Welker, 2005](#). In general, warm waters express higher  $\delta^{18}\text{O}$  isotopic ratios compared to colder waters ([McCrea, 1950](#), [Dansgaard, 1964](#)). In latitudes with seasonal temperature variation,  $\delta^{18}\text{O}$  ratios create a characteristic sinusoidal pattern related to the cyclical warmer and colder temperature variation through the year ([Balasse et al., 2002](#)).

Drinking behaviour directly influence the  $\delta^{18}\text{O}$  ratios expressed in dental enamel ([Kohn et al., 1996](#), [Levin et al., 2006](#)). Obligate drinkers such as equids, that access water daily ([Crowell-Davis et al., 1985](#), [Bahloul et al., 2001](#), [King, 2002](#), [Ogutu et al., 2010](#)), largely record the  $\delta^{18}\text{O}$  values of meteoric water, which is usually the primary drinking water source ([Bryant et al., 1994](#); [Hoppe et al. 2004](#); 2005). In that regard,  $\delta^{18}\text{O}$  values from modern horse enamel samples from different latitudes usually reflect the temperature and latitudinal variation in  $\delta^{18}\text{O}$  precipitation ([Bryant et al., 1994](#), [Chillón et al., 1994](#); [Delgado-Huertas et al., 1995](#), [Bell et al., 2006](#); [Stacy, 2008](#)). Nevertheless, the ingestion of  $^{18}\text{O}$  enriched water from small open water sources (e.g. water troughs) or  $^{18}\text{O}$  depleted groundwater from wells is known to influence  $\delta^{18}\text{O}$  values recorded in equid enamel ([Makarewicz et al. 2018](#)).

Because tooth enamel does not remodel once it is fully mineralized, sequential sampling along the growth axis of hypsodont (high-crowned) teeth records temporal variations in diet, climatic conditions and mobility during the time of enamel mineralisation. Consequently, equid teeth are suitable to analyse changes in diet, climatic conditions and mobility on a seasonal time scale, as it is done for other hypsodont

species (e.g. [Balasse et al., 2002](#), [Zazzo et al., 2002](#), [Balasse 2003](#), [Pederzani and Britton, 2019](#), [Passey and Cerling, 2002](#); [Balasse et al., 2012](#)).

## 2.3. Carbon isotopic ratios ( $\delta^{13}\text{C}$ ) in equid tooth enamel carbonates

Carbon isotopic ratios ( $\delta^{13}\text{C}$ ) from enamel carbonate are widely used to assess diet and foddering strategies both in wild and domestic herbivores (e.g. [Sullivan and Krueger, 1981](#), [Krueger and Sullivan, 1984](#), [Lee-Thorp et al., 1989](#), [Ambrose and Norr 1993](#), [Tieszen and Fagre, 1993](#), [Quade and Cerling, 1995](#); [Cerling et al., 1997](#); [Koch, 1998](#); [Tippie and Pagani, 2007](#)). The dominant factor influencing  $\delta^{13}\text{C}$  isotopic ratios is the photosynthetic pathway used for fixing carbon. C4 plants – typically tropical grasses, but also some plants from arid environments including millets (*Panicum miliaceum* and *Setaria italica*) – have relatively higher  $\delta^{13}\text{C}$  values than C3 plants commonly found in temperate areas because of an extremely efficient  $\text{CO}_2$  fixation ([Monson et al., 1984](#)). Consequently, plants using the C3 pathway have an average  $\delta^{13}\text{C}$  of  $-26\text{‰}$  PDB, while C4 plants express an average  $\delta^{13}\text{C}$  of  $-12\text{‰}$  PDB ([Smith and Epstein, 1971](#); [O'Leary, 1988](#), [Koch, 1998](#)).

Other factors that influence  $\delta^{13}\text{C}$  ratios are soil moisture, exposure to light and soil salinity among others ([Farquhar et al., 1982](#); [Farquhar and Von Caemmerer, 1982](#), [Farquhar, 1991](#), [Tieszen, 1991](#), [Heaton, 1999](#)). In general, a seasonal increase in  $\delta^{13}\text{C}$  ratios of C3 plants naturally occurs in summer linked to rainfall decrease and higher light exposure ([Smedley et al., 1991](#)). The contrary effect has been also observed on well-watered C3 cereals, which express more negative  $\delta^{13}\text{C}$  isotopic ratios compared to water-stressed ones ([Ferrio et al. 2005](#)). Similarly, areas with dense tree cover also have depleted  $\delta^{13}\text{C}$  values due to the canopy effect (e.g. [Farquhar et al., 1989](#); [Van der Merwe and Medina, 1991](#); [Ehleringer and Monson, 1993](#); [Passey et al., 2002](#)).

The formation of tooth enamel in herbivores entails a carbon isotopic fractionation of  $\sim 13\text{‰}$  ([Koch, 1998](#)). In domestic animals, carbon isotopic ratios  $\delta^{13}\text{C}$  from tooth enamel depend on all the factors mentioned above (i.e. the proportion of C4 and C3 plants in their diet, the degree of water availability, the vegetation cover in the grazing area). In addition,  $\delta^{13}\text{C}$  ratios will also depend on foddering practices (i.e. grass and straw cut in summer; e.g. [Makarewicz and Pederzani, 2017](#)) as well as the level of grain intake, as grains are enriched in  $^{13}\text{C}$  compared to straw ([Wallace et al., 2013](#)). The  $\delta^{13}\text{C}$  offset between grain and straw is calculated to be of  $+1.9\text{‰}$  for wheat (*Triticum aestivum durum*),  $+1.7\text{‰}$  for barley (*Hordeum vulgare*; [Wallace et al., 2013](#)), and about  $+2\text{‰}$  in millet (*Setaria italica*, [Lightfoot et al., 2020](#)). At Can Roqueta, the vegetation cover is dominated by C3 plants (e.g. barley, oak trees), although millets (*Panicum miliaceum* and *Setaria italica*) have been attested from the Bronze Age ([Albizuri et al., in press](#)).

## 2.4. Strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ )

Strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) are used as geographical proxy as they vary depending on the age of each geological formation, the original rubidium (Rb) content of the bedrock and the lithology of the rocks ([Capo et al. 1998](#)). In general, the more felsic and older a rock formation is, the higher the proportion of  $^{87}\text{Sr}$  will be ([Faure and Mensing 2005](#)). Strontium substitutes for calcium in skeletal tissues ([Bentley 2006](#)). Consequently, strontium isotope ratios from teeth and bones derive from the bioavailable strontium of the area where food was sourced ([Comar et al. 1957](#); [Toots and Voorhies 1965](#)). In archaeological remains, enamel bioapatite preserves the strontium isotope composition fixed during enamel mineralisation, thus providing direct evidence of geological origin and possible geographical variations during that time. In contrast, bone and dentine are more susceptible to diagenetic alteration (e.g. [Nelson et al. 1986](#); [Price et al. 2002](#); [Lee-Thorp and Sponeheimer 2003](#)) and their  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio progressively equilibrates with the one of the burial environment. Whether this equilibration is complete will depend on the conditions of the burial soil and how different

the original (biogenic)  $^{87}\text{Sr}/^{86}\text{Sr}$  was from that of the burial environment (see Nelson et al. 1986).

Previous comprehensive studies characterizing biogenic strontium isotopic ratios (e.g. Evans et al. 2010, Brönnimann et al. 2018, Willmes et al. 2018) suggest that present-day leaves from trees with deep roots located in undisturbed forests offer reliable data to characterise bioavailable strontium isotopic data. As the archaeological site of Can Roqueta is surrounded by motorways and industrial buildings, we used three dentine samples in addition to two present-day oak leaves in order to assess the strontium isotopic variability at the site (Fig. 3). Archaeological bone and dentine have proven to be reasonable proxies of the bioavailable strontium isotopic ratio present at archaeological sites (see e.g. Budd et al. 2000, Chiaradia et al. 2003, Viner et al. 2010, Minniti et al. 2014, Madgwick et al. 2019). The reference samples used in the present work for both Can Roqueta and nearby locations are the ones previously published in the pilot study (Albizuri et al. 2019, see also Valenzuela-Lamas et al. 2018, and Willmes et al. 2018 for the supra-regional range).

## 2.5. Data analysis and visualisation

R version 4.0.5 and packages ‘car’, ‘ggplot2’, ‘ggrepel’, ‘lattice’, ‘readxl’ and ‘stats’ have been used for data analysis, data visualisation and statistical testing (Fox 2007, Wickham 2011, Slowikowski et al. 2018, Sarkar et al. 2015, Wickham et al. 2019, R Core Team) building from R scripts facilitated by A. Trentacoste, T. Huet and A. Nieto-Espinet (see acknowledgments section). The lines uniting the dots in carbon and oxygen results (Figs. 4 and 5) were calculated with the function ‘spline’ (‘natural’ method) of the R package ‘stats’. The R code used to produce the figures is provided as supplementary material S3.

## 2.6. Sampling strategy on archaeological remains

Analysis of oxygen isotopic ratios ( $\delta^{18}\text{O}$ ) obtained from enamel carbonate has been shown to be robust in archaeological burial conditions (see Chenery et al., 2012 and references within). In latitudes where seasonal variations in temperature occur, the  $\delta^{18}\text{O}$  ratios provide a time frame related to the annual cycle that, in combination with carbon ( $\delta^{13}\text{C}$ ) and strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), can be used to detect foddering strategies and seasonal movements between different geological areas during the time of tooth formation (e.g. Balasse et al., 2002, Bentley and Knipper, 2005, Bogaard et al., 2013, Valenzuela-Lamas et al., 2016, Díaz-Zorita Bonilla et al., 2017).

A total of 28 teeth from Can Roqueta were sampled to assess equid provenance and strontium isotopic variability on other animals at the site (Table 1). Targeted sampling (one slice) was performed on 23 equid

teeth, one pig tooth, one dog tooth and three rabbit teeth. All the equid teeth were sampled on the mesial side and about 1 mm above the enamel root junction (ERJ) in order to have a stable point of comparison between individuals. Pig, dog and rabbit enamel was sampled as bulk. Carbon ( $\delta^{13}\text{C}$ ) and oxygen ( $\delta^{18}\text{O}$ ) isotopic ratios were also measured from the enamel slices analysed for strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ). In addition, three equid teeth were sequentially sampled for carbon ( $\delta^{13}\text{C}$ ), oxygen ( $\delta^{18}\text{O}$ ) and strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) in order to have a temporal sequence of isotopic variation and evaluate intra-tooth variability. In the case of individual EIA\_Eq\_94, both the third lower premolar (P3) and the third lower molar (M3) were analysed in order to assess inter-tooth variability and thus evaluate residential mobility during the time of enamel mineralisation.

Samples consisting of enamel slices c. 2–3 mm width were cut with a rotary micromotor. Each enamel sample was first mechanically cleaned with a dentist drill to remove all the dirt, tartar and dentine. Samples were then further carefully cleaned, chemically processed and analysed following standard procedures at the three geochemical labs involved in the analyses (see Pin et al. 1994, Díaz-Zorita Bonilla et al. 2020 and Valenzuela-Lamas et al., 2016 for more details). At the University of Montpellier, the Sr was purified at the SOTOP-MTP platform and then, the isotopic ratios were measured with a Neptune + Thermo Scientific Multi-Collector Inductively-Coupled-Plasma Mass Spectrometer (MC-ICP-MS) from the AETE-ISO platform (OSU OREME) under the supervision of D. Bosch. At the Curt Engelhorn Center for Archaeometry, Mannheim, Germany, Sr concentrations were determined by Quadrupole Inductively Coupled Plasma Mass Spectrometry (Q-ICP-MS), and the solutions diluted for strontium isotope analysis by High-Resolution Multi Collector-ICPMS (Neptune). At the University of Barcelona, Sr isotope samples were purified by standard chromatographic techniques at the Laboratori d'Isòtops Radiogenics i Ambientals (LIRA) and isotopic ratios were measured with a Nu Plasma 3 (PANTHALASSA) at the Centres Científics i Tecnològics de la Universitat de Barcelona (CCiT-UB) under the supervision of L.D. Pena. The results obtained in the three laboratories are in good agreement within the external reproducibility reported for all the analytical sessions (2sigma on NBS987 standard) and are coherent between samples (e.g. tooth EIA\_Eq\_P3\_294 and EIA\_Eq\_M3\_294 originate from the same individual and were analysed in Montpellier and Tübingen respectively, both showing similar results; see Table 1 and Fig. 4).

Samples for oxygen isotopic analysis ( $\delta^{18}\text{O}$ ) were obtained from enamel carbonate slices previously cleaned, as explained above for strontium analysis. The removal of organic material was done with 2% NaOCl solution for 24 h and then samples were placed in a 0.1 M Cacacetate acetic acid buffer solution for another 24 h and afterwards samples were rinsed and dried following standard protocols (Bocherens

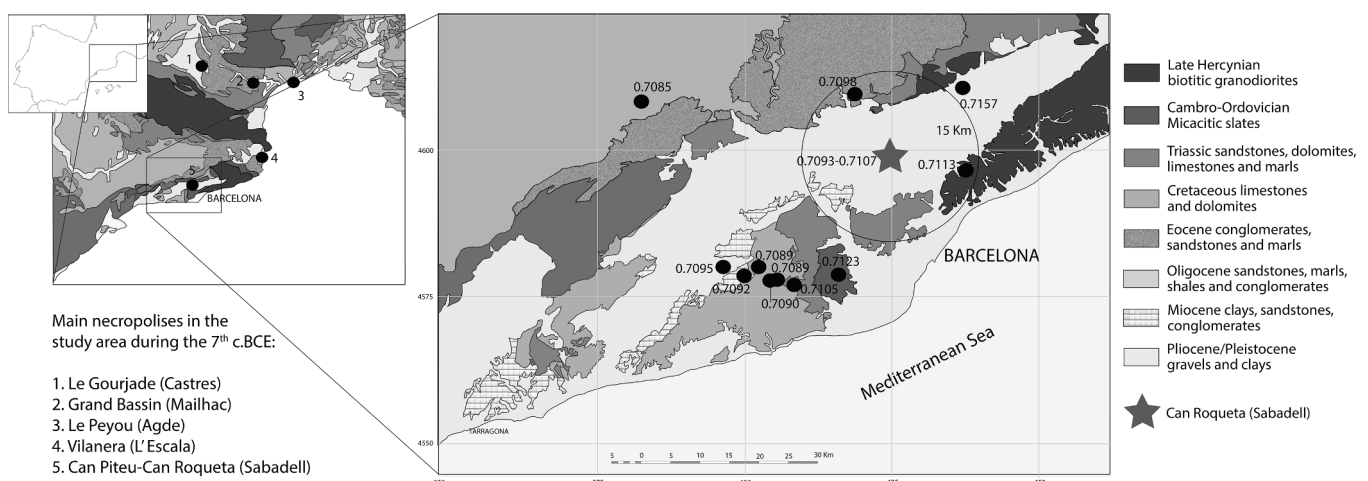


Fig. 3. Location of Can Roqueta (Sabadell, Barcelona) and variability of strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) around the site. The circle indicates a radius of 15 Km.

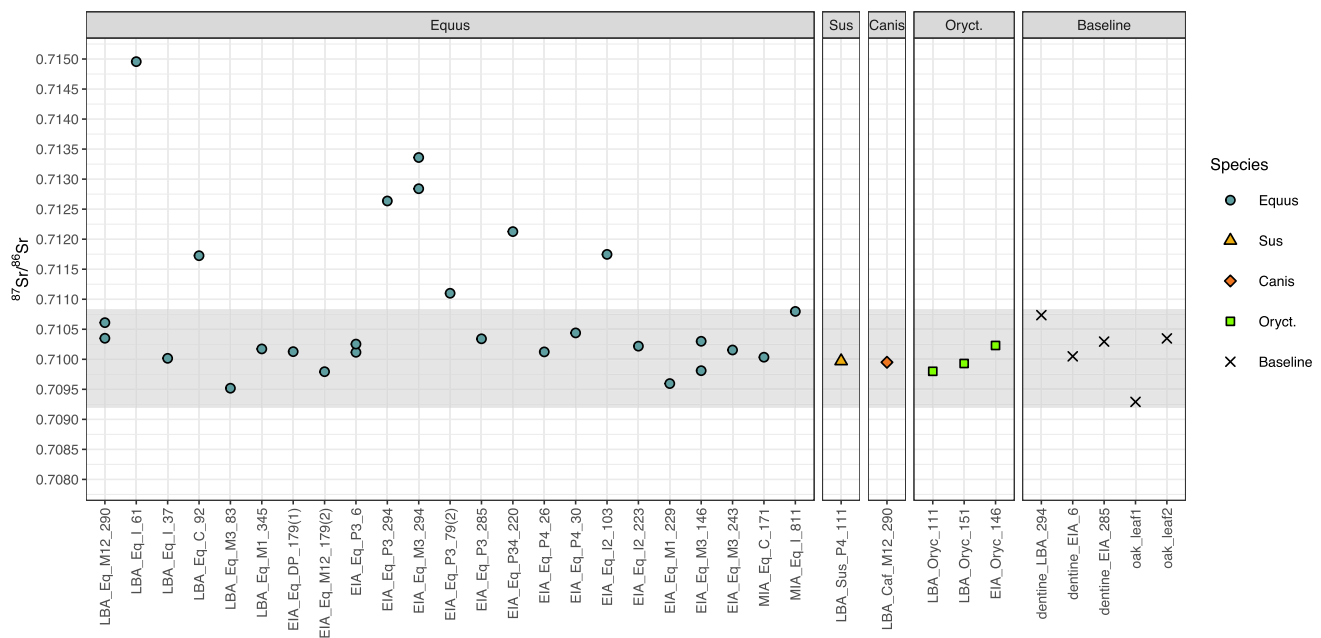


Fig. 4. Strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) registered in the 28 archaeological individuals from Can Roqueta and five reference samples.

et al. 1996). Samples were analysed using a Gasbench II on a Finnigan Delta Plus XL CF-IRMS at the University of Tübingen for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of the carbonate fraction. Isotopic abundances are expressed as  $\delta$  (delta) values in parts per mil (‰), as follows:  $\delta^{13}\text{C} = (^{13}\text{C}/^{12}\text{C}_{\text{sample}}/^{13}\text{C}/^{12}\text{C}_{\text{standard}} - 1) \times 1000$  and  $\delta^{18}\text{O} = (^{18}\text{O}/^{16}\text{O}_{\text{sample}}/^{18}\text{O}/^{16}\text{O}_{\text{standard}} - 1) \times 1000$ . The standards used are the marine carbonate V-PDB for carbon and oxygen and V-SMOW for oxygen. For fossil samples, the analytical error is 0.1–0.2‰ for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , based on multiple isotopic analysis of modern tooth enamel of camel and hippopotamus prepared and analysed at the same time.

For comparison with other studies, the values were also converted to the SMOW scale using the published conversion equation of (Coplen, 1988):  $\text{SMOW} = (1.03091 \times \delta^{18}\text{O VPDB}) + 30.91$ . Both carbon and oxygen VPDB values, together with carbonate oxygen results ( $\delta^{18}\text{O}$  SMOW) are presented in Table 1 and supplementary table S4.

### 3. Results

Table 1 presents all the information details for each sample analysed from Can Roqueta. Results from the former pilot study (Albizuri et al. 2019) have been integrated to present a more comprehensive picture on equid provenance and reference samples from the site.

#### 3.1. Strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) from equids and other species

Fig. 4 shows the strontium isotopic ratios obtained from each tooth, ordered by chronological period and species. Among the samples dated from the Late Bronze Age (1300–750 cal. BCE), two individuals (LBA\_Eq\_I\_61 and LBA\_Eq\_C\_92) had more radiogenic strontium isotopic ratios and likely arrived at the site from another location. They correspond to an unsexed equid aged of >9 years and a male of 5–7 years old (see details in Table 1). The individual LBA\_Eq\_M1/2\_290, for which an isolated lower M1 or M2 was sequentially sampled, had limited variability through its period of enamel mineralisation (7–37 months; Hoppe et al. 2004). Considering that the variability observed is compatible with the local strontium ratios attested at the different sectors of the site (sector codes detailed in Fig. 1), a local breeding of this animal is most plausible. Nevertheless, an origin from a nearby location or another geographical area with a similar geological composition

cannot be fully dismissed. This is also the case for the other individuals dated from the Late Bronze Age.

Most strontium isotopic ratios observed in Early Iron Age individuals (750–550 cal. BCE) are also compatible with the local isotopic range at the site. However, four individuals had more radiogenic values. Individual EIA\_Eq\_294 displayed high strontium isotopic ratios in the two teeth analysed (lower P3 and lower M3). This suggests that it was bred at a given location during the whole period of enamel mineralisation, and only arrived at Can Roqueta after the M3 was fully mineralised (>55 months; Hoppe et al. 2004). Individuals EIA\_Eq\_P3/4\_220 and EIA\_Eq\_I2\_103 also have more radiogenic strontium ratios than the ones observed from the reference samples. Considering the teeth analysed, individuals EIA\_Eq\_P3\_79(2) and EIA\_Eq\_P3/4\_220 were most probably fed on other geological locations between 14 and 36 months, and individual EIA\_Eq\_I2\_103 grazed on another lithology between 8 and 48 months (Miró et al. 2020).

The pig, the dog and the three analysed rabbits all had strontium isotopic ratios compatible with the ones attested from the reference samples. Therefore, it is most probable that they grew in the immediate surroundings of Can Roqueta.

Fig. 5 shows the strontium isotopic variability in the different periods and by species when considering only the sample located at the ERJ. Most animals have strontium isotopic ratios compatible with the local range attested at Can Roqueta. Some EIA equids have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios that fall in the 35 km range from the site. Only one individual dated from the LBA (Eq\_I\_61) has a strontium isotopic ratio that was recorded at the limit of the 35 km range (Valenzuela-Lamas et al. 2018). Statistical analyses (Levene's Test for homogeneity of variance) showed that the difference between the distribution of LBA and EIA equid samples is not significant ( $p = 0.6034$ ).

#### 3.2. Sequential and multi-isotopic sampling: carbon, oxygen and strontium isotopes

Fig. 6 displays the results obtained from the sequential sampling of enamel carbonate of three equids (oxygen, carbon and strontium isotopic ratios available in Table 1). The blue dots show the oxygen isotopic results ( $\delta^{18}\text{O}$ ), where highest  $\delta^{18}\text{O}$  values represent the warm season and the lowest  $\delta^{18}\text{O}$  values represent the cold season. The green dots refer to

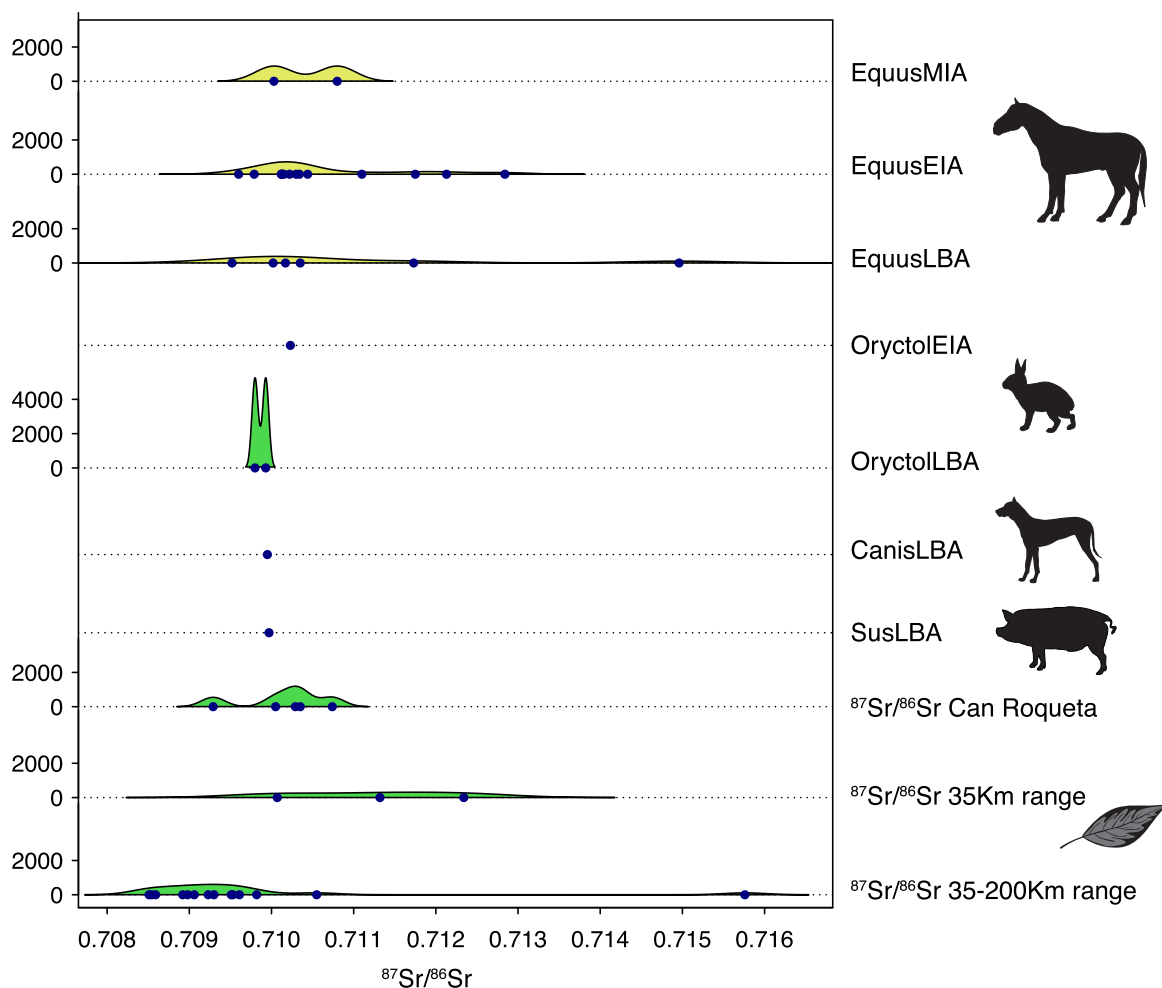


Fig. 5. Probability density function based on the strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) registered in the archaeological individuals from Can Roqueta per chronology and species, and distribution of the reference samples at the site, 35 Km range, and 35–200 Km range from the site. The grey band indicates the strontium isotopic range recorded at the site. Reference data from: Valenzuela-Lamas et al. 2018, Albizuri et al. 2019.

the  $\delta^{13}\text{C}$  isotopic ratios and the black dots refer to the strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ). The grey band shows the range of strontium isotopic ratios recorded at the site.

The mineralisation period of second and third equid molars spans almost three years (Hoppe et al. 2004), and the oxygen isotopic ratios recorded in the three teeth sequentially sampled (Fig. 6) reflect well the seasonal variation of temperature across more than one year (probably two years and a half on the two teeth dated from EIA). Although the number of samples is very limited to make inferences about seasonal mobility, the samples analysed for  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios in individuals LBA\_Eq\_M2\_290 and EIA\_EQ\_146\_M3 likely correspond to different seasons and are similar to the ones recorded on the dentine and leaf reference samples, while the two strontium samples from EIA\_Eq\_M3\_294 are much more radiogenic. The oxygen sequence in LBA\_Eq\_M2\_290 is too short to assess intra-tooth change oxygen variation (maximum ERJ 17 mm; min =  $-5.2\%$ , max =  $-3.9\%$ ), but LBA\_Eq\_M3\_146 has oxygen isotopic ratios between  $-6.6\%$ ,  $-4.6\%$  over 31 mm, and EIA\_Eq\_M3\_294 has oxygen isotopic ratios between  $-6.2\%$ ,  $-5.2\%$  over 32 mm, thus both showing an average amplitude of intra-tooth change of  $\Delta^{18}\text{O} = 2\%$ .

Carbon isotopic ratios ( $\delta^{13}\text{C}$ ) from these three teeth are diverse, which is consistent with the results obtained from bone collagen (see Grandal-d'Anglade et al., 2021 and Albizuri et al. 2021). In individual LBA\_EQ\_M2\_290, the degree of dental wear notably limited the temporal sequence, but the  $\delta^{18}\text{O}$  ratio corresponding to winter (ERJ = 17) is

highly opposed to the  $\delta^{13}\text{C}$  ratio while, subsequently, in the period likely corresponding to summer, both oxygen and carbon isotopic ratios seem positively correlated. As explained in the methods section,  $\delta^{13}\text{C}$  ratios tend to increase with aridity, which in Mediterranean climate usually corresponds to the seasonal variation that is also reflected on the oxygen isotopic ratios. This partial correlation between  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  is also visible in EIA\_EQ\_M3\_146: the first  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  ratios (ERJ > 20 mm) correlate, but in the first cold episode registered (ERJ = 17 mm) the animal was fed with a rich  $\delta^{13}\text{C}$  diet that subsequently decreased during the warm season (ERJ = 6 mm) and increased again in the second cold episode (ERJ = 1 mm). Individual EIA\_EQ\_M3\_294 shows a different picture. This is the equid with the most negative  $\delta^{13}\text{C}$  isotopic ratios (between  $-12.5\%$  and  $-12\%$ ). This animal probably had a diet based on C<sub>3</sub> grass and was given some grain or fodder cut during summer in the first cold episode registered (ERJ = 26 mm). Subsequently, it had a very stable feeding until the end of enamel mineralisation.

When comparing the carbon and oxygen isotopic ratios (Fig. 7), equid EIA\_EQ\_M3\_294 has similar values as the rabbits analysed, while the majority of equids have much higher oxygen and carbon isotopic ratios. The only exception is individual MIA\_Eq\_C\_171, which also has rather low carbon and oxygen isotopic ratios compared with the rest of equids. Interestingly, the analysed pig (LBA\_Sus\_P4\_111) has higher carbon isotopic values than the dog (LBA\_Caf\_M12\_290) thus suggesting that pigs may have had access to more subproducts from C<sub>4</sub> plants (domestic garbage?). The differences in both  $\delta^{13}\text{C}$  carbon and  $\delta^{18}\text{O}$



**Table 1**  
Isotopic results (strontium  $^{87}\text{Sr}/^{86}\text{Sr}$ , oxygen  $\delta^{18}\text{O}$  and carbon  $\delta^{13}\text{C}$ ) and main context details of each of the samples included in this study.

Species	Description	Tooth	Mineralisation period (Hoppe et al. 2004)	Distance ERJ	$^{87}\text{Sr}/^{86}\text{Sr}$	2 sigma	$\delta\text{C13\_PDB}$	$\delta\text{O18\_PDB}$	SMOW	CO3 (%)	Lab	Publication
Equus	Enamel	LBA_Eq_M12_290	7–37 months	17–21 mm	0.71061	0.00003	−9.7	−3.9	26.9	3.9	Tubingen	This paper
Equus	Enamel	LBA_Eq_M12_290	7–37 months	12–14 mm			−9.1	−5.2	25.5	3.6	Tubingen	This paper
Equus	Enamel	LBA_Eq_M12_290	7–37 months	7–10 mm			−7.8	−4.7	26.0	3.8	Tubingen	This paper
Equus	Enamel	LBA_Eq_M12_290	7–37 months	0–3 mm	0.71035	0.00001	−8.6	−5.0	25.7	3.4	Tubingen	This paper
Equus	Enamel	LBA_Eq_I_61		2–4 mm	0.71496	0.00001					Montpellier	This paper
Equus	Enamel	LBA_Eq_I_37		2–4 mm	0.71002	0.00000	−9.94	−2.13	28.67	5.79	Montpellier	This paper
Equus	Enamel	LBA_Eq_C_92		2–4 mm	0.71173	0.00000	−12.49	−5.39	25.30	5.20	Montpellier	This paper
Equus	Enamel	LBA_Eq_M3_83	21–55 months	2–4 mm	0.70952	0.00000	−11.58	−1.69	29.12	5.45	Montpellier	This paper
Equus	Enamel	LBA_Eq_M1_345	0.5–23 months	2–4 mm	0.71017	0.00003	−9.09	−2.54	28.25	6.25	UB	This paper
Equus	Enamel	EIA_Eq_M12_179(2)	0.5–23 months	2–4 mm	0.70979	0.00001	−9.38	−3.15	27.61	6.07	Montpellier	This paper
Equus	Enamel	EIA_Eq_P3_6	14–36 months	2–4 mm	0.71012	0.00001	−9.19	−2.50	28.28	5.43	Montpellier	This paper
Equus	Enamel	EIA_Eq_P3_6	14–36 months	2–4 mm	0.71025	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_P3_294	14–36 months	2–4 mm	0.71264	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_M3_294	21–55 months	31–34 mm	0.71336	0.00002	−12.4	−5.3	25.4	2.9	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	26–28 mm			−12.0	−6.2	24.5	2.6	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	22–24 mm			−12.4	−5.9	24.8	3.0	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	16–19 mm			−12.4	−5.9	24.8	3.0	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	12–14 mm			−12.4	−6.0	24.7	2.9	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	8–10 mm			−12.5	−5.2	25.5	3.4	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	4–6 mm			−12.2	−5.3	25.4	3.5	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_294	21–55 months	0–2 mm	0.71284	0.00002	−12.5	−6.2	24.5	3.6	Tubingen	This paper
Equus	Enamel	EIA_Eq_P3_79(2)	14–36 months	2–4 mm	0.71110	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_P3_285	14–36 months	2–4 mm	0.71034	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_P34_220	14–36 /19–51 months	2–4 mm	0.71213	0.00000	−8.62	−2.94	27.83	7.06	Montpellier	This paper
Equus	Enamel	EIA_Eq_P4_26	19–51 months	2–4 mm	0.71012	0.00001	−7.79	−2.64	28.13	6.10	UB	This paper
Equus	Enamel	EIA_Eq_P4_30	19–51 months	2–4 mm	0.71044	0.00001	−6.23	−3.55	27.20	6.29	Montpellier	This paper
Equus	Enamel	EIA_Eq_I2_103		2–4 mm	0.71175	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_I2_223		2–4 mm	0.71022	0.00001					Montpellier	Albizuri et al 2019
Equus	Enamel	EIA_Eq_M1_229	0.5–23 months	2–4 mm	0.70960	0.00000	−10.91	−2.33	28.46	5.70	Montpellier	This paper
Equus	Enamel	EIA_Eq_DP_179(1)		2–4 mm	0.71013	0.00001	−8.94	−2.68	28.09	6.02	Montpellier	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	31–34 mm	0.70981	0.00001	−10.9	−6.6	24.1	3.8	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	26–29 mm			−8.5	−6.1	24.6	3.5	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	21–23 mm			−6.6	−5.1	25.6	3.9	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	17–19 mm			−5.6	−5.7	24.9	3.5	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	12–15 mm			−6.2	−5.2	25.5	3.9	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	7–10 mm			−7.1	−4.6	26.1	3.5	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_146	21–55 months	0–5 mm	0.71030	0.00002	−5.6	−5.7	25.0	3.3	Tubingen	This paper
Equus	Enamel	EIA_Eq_M3_243	21–55 months	2–4 mm	0.71015	0.00000	−8.84	−3.88	26.86	6.32	Montpellier	This paper
Equus	Enamel	MIA_Eq_C_171		2–4 mm	0.71003	0.00001	−11.81	−4.72	25.99	5.80	Montpellier	This paper
Equus	Enamel	MIA_Eq_I_811		2–4 mm	0.71080	0.00004	−7.31	−3.65	27.10	5.40	UB	This paper
Sus	Enamel	LBA_Sus_P4_111	19–51 months	bulk	0.70997	0.00001	−10.2	−7.3	23.3	2.6	Tubingen	This paper
Canis	Enamel	LBA_Caf_M12_290	7–37 months	bulk	0.70995	0.00002	−11.8	−7.4	23.3	3.0	Tubingen	This paper
Oryct.	Enamel	LBA_Oryc_151		bulk	0.70993	0.00003	−13.2	−5.2	25.5	4.1	Tubingen	This paper
Oryct.	Enamel	LBA_Oryc_111		bulk	0.70980	0.00002	−12.9	−6.3	24.4	3.8	Tubingen	This paper
Oryct.	Enamel	EIA_Oryc_146		bulk	0.71023	0.00001	−12.4	−6.2	24.5	3.5	Tubingen	This paper
Baseline	oak leaf	oak_leaf1			0.70929	0.00001					Montpellier	Albizuri et al 2019
Baseline	oak leaf	oak_leaf2			0.71035	0.00000					Montpellier	Albizuri et al 2019
Baseline	dentine	dentine_EIA_6			0.71005	0.00000					Montpellier	Albizuri et al 2019
Baseline	dentine	dentine_EIA_285			0.71029	0.00001					Montpellier	Albizuri et al 2019
Baseline	dentine	dentine_LBA_294			0.71074	0.00001					Montpellier	Albizuri et al 2019

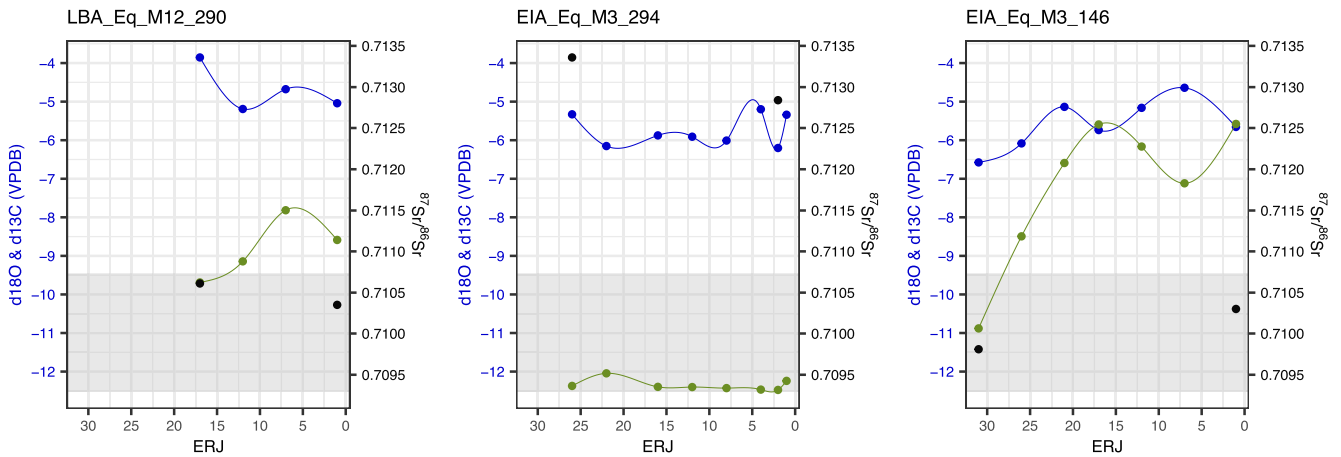


Fig. 6. Isotopic oxygen ( $\delta^{18}\text{O}$ ), carbon ( $\delta^{13}\text{C}$ ) and strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) ratios registered on the three equid teeth sequentially sampled. The grey band shows the strontium isotopic range obtained on the reference samples from Can Roqueta (isotopic ratios available in Table 1).

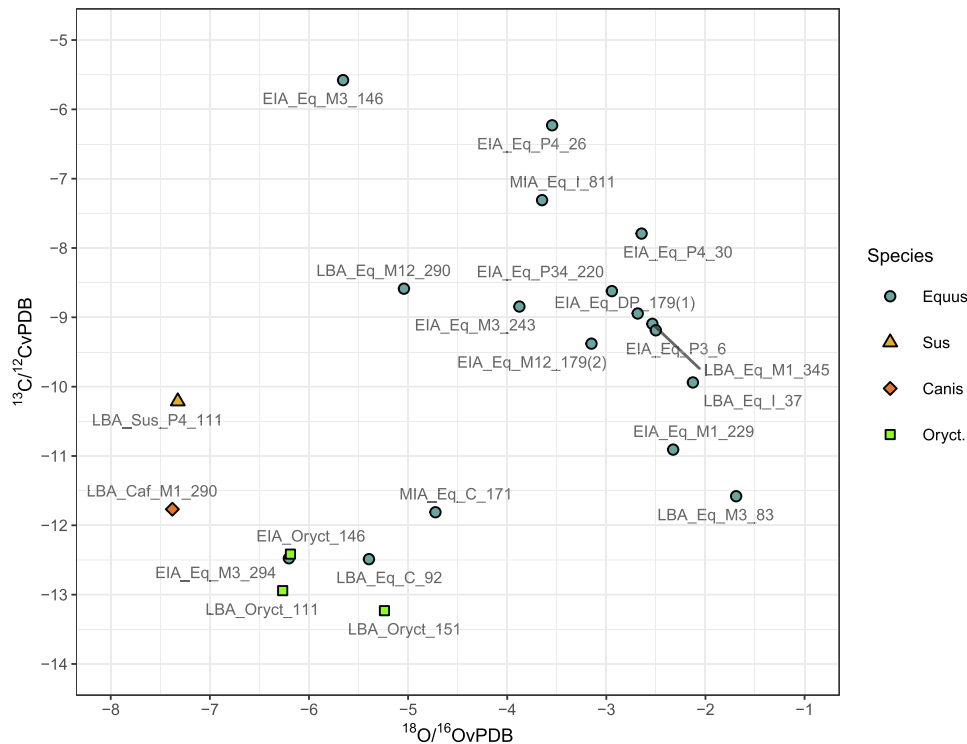


Fig. 7. Isotopic carbon ( $\delta^{13}\text{C}$ ) and oxygen ( $\delta^{18}\text{O}$ ) ratios registered on the different animal species at Can Roqueta (isotopic values from Table 1). Values from the samples located close to ERJ.

oxygen isotopic ratios between equids and the other animal species were found to be significant (Kruskal-Wallis test on  $\delta^{13}\text{C}$ , p-value = 0.0108; Kruskal-Wallis test on  $\delta^{18}\text{O}$ , p-value = 0.0025).

#### 4. Discussion

The sampling strategy was designed to maximise the number of equids analysed to assess equid breeding and provisioning while exploring the possibility of seasonal dietary changes and residential mobility. Accordingly, strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), carbon ( $\delta^{13}\text{C}$ ) and oxygen ( $\delta^{18}\text{O}$ ) samples were taken from the majority of individuals represented by complete dental series near the enamel root junction (ERJ; see Table 1) to obtain pure enamel samples. In addition, three equids were

targeted for sequential sampling to investigate intra-individual changes in mobility and diet during the time of enamel mineralisation by combining carbon ( $\delta^{13}\text{C}$ ) oxygen ( $\delta^{18}\text{O}$ ) and strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotopic ratios along the tooth crown. This multi-isotopic approach provides valuable data about equid sourcing and managing in NE Iberia during Late Prehistory.

##### 4.1. Equid sourcing - the strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) evidence

Most animals were found to express strontium isotopic ratios compatible with the ones registered by reference samples (dentine and present-day leaves) from Can Roqueta. This applies to most equids but also to the pig, the dog and the three analysed rabbits, which most

probably were reared / sourced locally. Five out of the 22 equids analysed had more radiogenic strontium isotopic ratios than the ones measured on the reference samples from the site. Equid LBA\_Eq\_I\_61 expressed the highest strontium isotopic ratio ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.71496$ , 2 s std. dev = 0.00001, see Table 1) only recorded so far in the Montseny massif (Valenzuela-Lamas et al. 2018). Also, Equid EIA\_Eq\_294 was born and reared outside the local geological area and brought to the site after the mineralisation of all the teeth was complete (as observed in P3 and M3 –Fig. 4– and also at the sequential results for M3 on Fig. 6). This supports the hypothesis some individuals may have arrived to the site as ‘finished products’, already tamed and trained (Albizuri et al. 2019). The absence of juvenile and subadult equid remains among the animals deposited in the 120 excavated pits contrasts with the presence of juvenile individuals of other species (e.g. dogs, caprines, pigs), and suggests that equids may originate from the surroundings of the site. Alternatively, if bred within the site, the carcasses of accidental deaths of juvenile equids may have been deposited in other areas and not in the pits, although this seems more unlikely (Albizuri et al. 2019).

#### 4.2. Adding to the picture: The oxygen ( $\delta^{18}\text{O}$ ) data

From the strontium results alone, it is not possible to discriminate between a rearing in Vallès or other neighbouring areas with Pliocene bedrock such as Valencia or the Gulf of Lion (strontium isotopic ratios for France available in Willmes et al. 2018). Oxygen isotopic ratios are also similar between the two areas, although in present times they tend to be slightly more negative in southern France compared to Vallès (see Lightfoot and O’Connell, 2016). At Can Roqueta,  $\delta^{18}\text{O}$  ratios range from  $-6.6\text{‰}$  and  $-1.7\text{‰}$  in equid enamel, and between  $-7.4\text{‰}$  and  $-5.2\text{‰}$  in other animal species (a dog, a pig and three rabbits). The three equid teeth sequentially sampled from Can Roqueta have ranges between  $-6.6\text{‰}$  and  $-3.9\text{‰}$ , and an average amplitude of intra-tooth change of  $\delta^{18}\text{O} = 2\text{‰}$ .

The pig, the dog and the three rabbits analysed likely reflect the temperature conditions at Can Roqueta on the basis of their oxygen isotope ratios (see Table 1) and Fig. 7), taking into account the unlikelihood that the rabbits came from distant locations due to the abundance of this taxon in Iberia. These are lower oxygen isotopic ratios than the values observed at other sites in the Gulf of Lion. At Neolithic La Draga (Banyoles), located 90 km to the north and slightly more inland, cattle show minimum and maximum  $\delta^{18}\text{O}$  ratios of  $-3.4\text{‰}$  and  $-0.1\text{‰}$  respectively, with a mean amplitude of intra-tooth change of  $\delta^{18}\text{O} = 2.1\text{‰}$  (Navarrete et al. 2019). Caprines from this site have minimum and maximum  $\delta^{18}\text{O}$  ratios of  $-4\text{‰}$  and  $2.2\text{‰}$ , and a mean amplitude of intra-tooth change of  $\delta^{18}\text{O} = 2.7\text{‰}$  (Navarrete et al. 2019). Also in this area (Gulf of Lion), Knockaert et al. (2018) attested oxygen isotopic ratios between  $-6.7\text{‰}$  and  $1.3\text{‰}$  in Bronze Age caprine enamel carbonate from Llo (1300 m above the sea level, Cerdagne, Eastern Pyrenees; 1430–1231 cal. BCE), and between  $-3.3$  and  $0\text{‰}$  at coastal Portal-Viehl (Vendres, Hérault; radiocarbon dates between 1211 and 1020 cal BCE and 820–594 cal BCE; Knockaert et al. 2018).

Consequently, oxygen isotopic ratios at Can Roqueta are generally lower than the ones attested in other sites at the Gulf of Lion. The oxygen isotopic ratios from these works are fairly comparable with ours as the pre-treatment protocols are the same (see methods section). Given that  $\delta^{18}\text{O}$  ratios are mainly dependent on temperature, the ratios attested at Can Roqueta suggest that temperature at the site was probably lower compared with Neolithic La Draga and Early Iron Age Portal-Viehl, and similar to the temperature at Early Bronze Age Llo (although the oxygen ratios in Can Roqueta are lower than the ones attested at Llo, see values above).

It is known that the Bronze Age was marked with climatic instability in Western Europe (Magny et al. 2009). Around 1650–1350 BCE, a temperature cooling of about  $0.7\text{ °C}$  and increasing annual rainfall (about 70–100 mm) is attested in the Western Mediterranean (Magny et al. 2009). Weather conditions worsened again around 850 BCE (van

Geel et al. 1996, Magny et al. 2007). This could explain the lower oxygen isotopic ratios registered at Can Roqueta during the LBA/EIA compared with the Neolithic and Early Bronze Age data. Nevertheless, the oxygen isotopic ratios attested in Can Roqueta raise several questions. One is the difference between the pig, the dog and the three rabbits ( $\delta^{18}\text{O}$  between  $-7.4\text{‰}$  and  $-5.2\text{‰}$ ) and the analysed equids ( $\delta^{18}\text{O}$  between  $-6.6\text{‰}$  and  $-1.7\text{‰}$ ), which was found to be significant (Kruskal-Wallis test, p-value = 0.002). Rabbits are thought to provide enriched  $\delta^{18}\text{O}$  ratios because their small size, the low amount of water intake and the high proportion of grass intake (Delgado-Huertas et al., 1995). This contrasts with equids, that are obligate drinkers and provide better relation to  $\delta^{18}\text{OH}_2\text{O}$  (Hoppe et al. 2004, van Dam & Reichart 2009). The rabbit  $\delta^{18}\text{O}$  ratios at Can Roqueta are higher than the ones obtained on the pig and the dog and, therefore, potentially enriched. But they are definitively lower than the equid  $\delta^{18}\text{O}$  ratios, except for individual EIA\_EQ\_M3\_294. This opens several possible scenarios: most horses originate from an area with higher  $\delta^{18}\text{O}$  ratios (and so, potentially, warmer temperatures than Can Roqueta). Alternatively, most horses could drink warm water during the period of enamel mineralisation. The intake of warm water ( $18\text{ °C}$ ) in cold conditions is encouraged in some cases to prevent abdominal colic (Kristula & McDonnell 1994). Nevertheless, the  $\delta^{18}\text{O}$  amplitude attested on the three equid teeth sequentially sampled is coherent with seasonal variation and, therefore, the hypothesis of warm water intake seems improbable. A third possible scenario is that equids drank from water troughs rather than directly from nearby streams. This could entail a carbon and oxygen isotopic enrichment due to evaporation (Talbot 1990, Horton et al. 2016, Makarewicz et al. 2018, similar to a ‘lake’ effect), which could explain the observed higher carbon and oxygen values from equid teeth (Figs. 6 and 7). Finally, the enrichment could originate from a metabolic fractionation, as higher  $\delta^{18}\text{O}$  ratios in equids compared to bovids have been recorded in some Pleistocene individuals (e.g. Roche et al. 2013, prof. Julia Lee-Thorp pers. comm.), although this is not fully consistent across regions (e.g. Feranec et al. 2009). Consequently, the combined  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  isotopic ratios could reflect that equids may not originate from Vallès, but equid rearing in the surroundings of the site is also plausible.

If we consider an external origin of the equids (albeit from an area with similar geology as Vallès), the connection between Vallès, Empordà and Languedoc-Roussillon is well attested based on metallic objects and funerary traditions. In particular, the necropolis of Grand Bassin in Mailhac and the three necropolises of Castres and Le Peyrou in Agde are very similar to the necropolis of Can Piteu-Roqueta (Rovira and López-Cachero, 2016). Moreover, the lead isotope analyses performed on some bronze objects from the necropolis of Can Piteu-Roqueta (i.e. a Mialhacian arrowhead, and a double-spring fibula) show the probable use of copper ores from the area of Les Cévennes (Rovira et al., 2008; Rovira and López-Cachero 2016), which could be a potential area of origin for the equids recovered at Can Roqueta given the underlying geology (Willmes et al. 2018). Previous studies on equid mobility in other areas (e.g. Bendrey et al. 2009, Makarewicz et al. 2018) attested that equids may have been sourced from considerable distances. Unfortunately, there is a lack of published isotopic data from other neighbour areas like Valencia, the occidental plain in Catalonia and the Empordà valley. Future studies expanding the number of strontium and oxygen isotopic data from Iberia and Southern France will allow us to provide a better assessment about possible places of origin of the equids from Can Roqueta.

#### 4.3. Carefully managed: The carbon isotopic data ( $\delta^{13}\text{C}$ )

The low carbon isotopic ratios attested in the three rabbits and equid EIA\_EQ\_294\_M3 (Fig. 7) reflect a major contribution of  $\text{C}_3$  plants in diet, assuming an enrichment factor of  $+13\text{‰}$  between dietary uptake and dental enamel (Koch, 1998). Environment at Can Roqueta and, more largely, at the area of the Gulf of Lion, is  $\text{C}_3$  plants dominant (Riera-Mora and Esteban-Amat, 1994, Pyankov et al. 2010). However,  $\text{C}_4$  millets are

also attested in the region from the Bronze Age (Alonso 1999), and millets grains (*Panicum miliaceum* and *Setaria italica*) are attested at Can Roqueta from the LBA and their presence increased during EIA (Albizuri et al., in press).

At Can Roqueta, most equids have significantly higher  $\delta^{13}\text{C}$  ratios compared to other animal species (Kruskal-Wallis test,  $p$ -value = 0.006), and many have  $\delta^{13}\text{C}$  above  $-10\text{‰}$  (Fig. 7). This may have different origins that can potentially occur simultaneously: the high  $\delta^{13}\text{C}$  isotopic ratios could derive from influence of C4 plants in their diet (Balasse et al. 2013) or from significant grain intake, which is  $\delta^{13}\text{C}$  enriched compared to straw about  $+1.9\text{‰}$  in wheat (*Triticum aestivum durum*),  $+1.7\text{‰}$  in barley (*Hordeum vulgare*; Wallace et al., 2013), and about  $+2\text{‰}$  in millet (*Setaria italica*, Lightfoot et al. 2020). In addition, high  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic ratios can be related to water management strategies, as equids could drink from water troughs rather than directly from streams as discussed above.

The three teeth sequentially sampled offer a detailed and interesting picture of how equid diet may have been managed through the time of enamel mineralisation. In that regard, the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  covariances observed on the three teeth (Fig. 6) suggest that the three equids received fodder supply (either grass cut in summer, millet and/or grain) during the winter months, thus suggesting that equid diet was carefully managed through the year to ensure the wellbeing of the animals. The stability of the  $\delta^{13}\text{C}$  isotopic ratios along the tooth crown in EIA\_Eq\_M3\_294 also suggests a strongly managed diet through the year, even if in this case it was rather depleted on  $\delta^{13}\text{C}$  (Figs. 6 and 7).

The lower  $\delta^{13}\text{C}$  ratios on EIA\_Eq\_M3\_294 may be related to the absence of grain or C<sub>4</sub> plant apports, and they could also reflect the canopy effect in forested areas, that can entail  $\delta^{13}\text{C}$  depletions between 3 ‰ and 5.6 ‰ (Farquhar et al., 1989). According to strontium isotopic ratios ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.7126\text{--}0.7134$ ), this equid originates from a more radiogenic area – probably from a granitic lithology–. In addition, the slightly lower  $\delta^{18}\text{O}$  ratios also suggest that this equid either originates from a slightly colder area or it drank from a colder water source. The combination of these three elements (C, Sr, O) strongly suggests a ‘foreign’ origin for this individual, most probably from an area with a granitic lithology, well-watered and/or densely forested, and slightly colder than the surroundings of Can Roqueta. A granitic massif with cold-temperate climate– Montseny area, 1712 m a.s.l. – can be found 50 Km north of Can Roqueta. Other granitic areas with cold-temperate climate in this area can be found in the Pyrenees, located 150–180 km from the site (e.g. Puigmal and Canigó areas, and also further west to Pica d’Estats). Interestingly, the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  ratios of this individual (EIA\_EQ\_M3\_294) are similar to the rabbits from Can Roqueta.

Overall, the  $\delta^{13}\text{C}$  isotopic data from enamel suggest that equid diet and watering was carefully supervised all the yearlong, and most notably in winter, to guarantee the well-being of the animals. To that end, not a sole enamel hypoplasia was observed in the equid dental material from Can Roqueta, which contrasts with the existence of some pathologies related to effort related to traction and bit wear (Albizuri et al. 2019).

## 5. Conclusion

This is the most comprehensive study on equid sourcing and mobility so far in Iberia. The combined multi-isotopic information from strontium, carbon and oxygen isotopic ratios suggests that equids were sourced from mainly local areas, but probably included different locations. Equids were carefully managed, most notably in winter. The higher carbon and oxygen ratios from equid teeth compared with other taxa could reflect that equids drank from water troughs rather than directly from neighbour streams, which would lead to an isotopic enrichment due to evaporation. Nevertheless, higher carbon isotopic ratios may also occur due to high grain intake, and some oxygen enrichment has been observed in wild equid populations (Roche et al. 2013). Finally, an origin from another location with a similar geology

and warmer temperatures cannot be completely excluded.

This multi-isotopic analysis highlights the importance and the need of further investigation using biochemical studies to assess animal management during Late Prehistory, and the various factors that can have an impact on isotopic ratios in animal teeth.

## Declaration of Competing Interest

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

## Data availability

Data and code are available as [supplementary material](#)

## Acknowledgements

This research was part of the research undertaken by the consolidated research group 2021SGR-00337 Seminari d’Estudis i Recerques Prehistòriques (SERP-UB), and was funded by Ministerio de Economía y Competitividad of Spain, within the projects HAR2017-87695-P (PI: J. López Cachero) and HAR2015-67323-C2-1-P (PI: M.E. Subirà Galdácano). The research was also supported by ERC-StG 716298 (PI: S. Valenzuela-Lamas). We thank Drs. Angela Trentacoste, Thomas Huet and Ariadna Nieto-Espinet for facilitating R scripts developed during ERC-StG 716298 (Huet, T. et al. (2022). Zoowork (Version 0.0.0.9000) [Computer software]. [10.5281/zenodo.6850736](https://doi.org/10.5281/zenodo.6850736)), and we thank J.M. Pozo for his guidance when tailoring the scripts to the present research. The R markdown script related to the present work is accessible in [supplementary file S4](#). We also thank prof. Julia Lee-Thorp for pointing the possible oxygen enrichment effect in equids and suggesting relevant literature. Finally, we thank the three anonymous reviewers whose comments significantly improved the paper.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2023.104032>.

## References

- Albizuri, S., 2014. La visibilitat del cavall en el registre arqueològic del NE peninsular durant el final de l’edat del bronze i la primera edat del ferro. L’exemple de Can Roqueta (Sabadell, Vallès Occidental), La transició bronze final - primera edat del ferro en els Pirineus i territoris veïns, *XV Col·loqui Internacional de Puigcerdà*. Puigcerdà 579–593.
- Albizuri, S., Alonso, N., López Cachero, F.J. 2011. Economía i canvi social a Catalunya durant l’edat del bronze i la primer edat del ferro, in: Valenzuela-Lamas, S., Padrós, N., Belarte, M.C., Sanmartí, J. (Eds.), *Economía agropecuària i canvi social a partir de les restes bioarqueològiques. El primer mil·lenni aC a la Mediterrània occidental*, V Reunión Internacional d’Arqueologia de Calafell, Abril 2009, Arqueo Mediterrània 12, 11–36.
- Albizuri, S., Grandal, A., Terrats, N., Oliva, M., Majó, T., Antolín, F., López-Cachero, J. (in press). Continuity and innovation in human diets through bioarchaeological analysis. The community of Can Roqueta in the pre-coastal of Barcelona and its Mediterranean contacts, 8th–6th centuries BC. *Mixed Tastes: Diets, Cuisines and Consumption Practices in Ancient Western Mediterranean*, Babesch. Annual Papers of Mediterranean Archaeology.
- Albizuri, S., Valenzuela-Lamas, S., Bosch, D., Fernandez, M., López-Cachero, F.J., 2019. Equid use and provision during the Early Iron Age in Can Roqueta (NE Iberian Peninsula). *Zoarchaeological study and first strontium isotope result ( $^{87}\text{Sr}/^{86}\text{Sr}$ )*. *J. Archaeol. Sci. Rep.* 26, 101907.
- Albizuri, S., Grandal-D’Anglade, A., López-Cachero, F.J., 2021. Pastures and fodder for feeding equids 3000 years ago. the Can Roqueta site (Barcelona, Spain) as a model of equine herd management. *Int. J. Osteoarchaeol.* 1–12.
- Albizuri, S. 2008. “Informe de l’estudi arqueozoològic de Can Roqueta / Can Revella 2008 (Sabadell i Barberà del Vallès, Vallès Occidental)”. In Terrats, N.; Oliva, M. (2009). *El jaciment arqueològic de Can Roqueta-Can Revella (Sabadell i Barberà del Vallès, Vallès Occidental) 2005/2006*. Vol. II. Barcelona: Departament de Cultura, Servei d’Arqueologia: Generalitat de Catalunya. Estudi complementari. Faunal report.

- Alonso, N., 1999. *De la llavor a la farina: els processos agrícoles protohistòrics a la Catalunya Occidental* (Monographies d'Archéologie Méditerranéenne 4). Centre National de la Recherche Scientifique, Lattes.
- Antolín, F., 2008. Informe preliminar dels resultats de la flotació, la tria i la identificació carpòlica del jaciment de Can Roqueta - Can Revella. de Prehistòria, Universitat Autònoma de Barcelona, unpublished carpological report, Dept.
- Bahloul, K., Pereladova, O.B., Soldatova, N., Fisenko, G., Sidorenko, E., Sempéré, A.J., 2001. Social organization and dispersion of introduced kulans (*Equus hemionus* kulan) and Przewalski horses (*Equus przewalski*) in the Bukhara Reserve, Uzbekistan. *J. Arid Environ.* 47 (3), 309–323.
- Balasse, M., 2003. Potential biases in sampling design and interpretation of intra-tooth isotope analysis. *Int. J. Osteoarchaeol.* 13 (1–2), 3–10.
- Balasse, M., Ambrose, S.H., Smith, A.B., Price, T.D., 2002. The seasonal mobility model for prehistoric herders in the south-western Cape of South Africa assessed by isotopic analysis of sheep tooth enamel. *J. Archaeol. Sci.* 29 (9), 917–932.
- Balasse, M., Obein, G., Ughetto-Monfrin, J., Mainland, I., 2012. Investigating seasonality and season of birth in past herds: a reference set of sheep enamel stable oxygen isotope ratios. *Archaeometry* 54 (2), 349–368.
- Balasse, M., Bălăşescu, A., Janzen, A., Ughetto-Monfrin, J., Mirea, P., Andreescu, R., 2013. Early herding at Măgura-Boldul lui Moş Ivănuş (early sixth millennium BC, Romania): environments and seasonality from stable isotope analysis. *Eur. J. Archaeol.* 16 (2), 221–246.
- Bell, L.S., Lee-Thorp, J.A., Dobney, K., 2006. Mapping human movement using stable oxygen isotopic ratio mass spectrometry: potential application to forensic science demonstrated by a modern horse-human study. *Can. Soc. Forensic Sci.* 39 (2), 47–54.
- Bendrey, R., 2010. The Horse. In: O'Connor, T., Sykes, N. (Eds.), *Extinctions and Invasions*. Oxbow Books, Windgather Press, Oxford, A social history of British fauna, pp. 10–16.
- Bendrey, R., Hayes, T.E., Palmer, M.R., 2009. Patterns of Iron Age horse supply: an analysis of strontium isotope ratios in teeth. *Archaeometry* 51 (1), 140–150.
- Bentley, R.A., Knipper, C., 2005. Transhumance at the early Neolithic settlement at Vaihingen (Germany). *Antiquity* 79 (306), 1–3.
- Bentley, R.A., 2006. Strontium isotopes from the earth to the archaeological skeleton: a review. *J. Archaeol. Method Theory* 135–187.
- Bocherens H, Koch PL, Mariotti A, Geraads D, Jaeger JJ 1996 Isotopic biogeochemistry (13C, 18O) of mammal enamel from African Pleistocene hominid sites: implications for the preservation of paleoclimatic isotopic signals. *Palaios* 11:306–18.10.2307/3515241.
- Bogaard, A., Fraser, R., Heaton, T.H., Wallace, M., Vaiglova, P., Charles, M., Stephan, E., 2013. Crop manuring and intensive land management by Europe's first farmers. *Proc. Natl. Acad. Sci.* 110 (31), 12589–12594.
- Bronk Ramsey, C. 2023. OxCal v4.4.4. Available at: <https://c14.arch.ox.ac.uk/oxcal.html>.
- Bryant, J.D., Luz, B., Froelich, P.N., 1994. Oxygen isotopic composition of fossil horse tooth phosphate as a record of continental paleoclimate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 107 (3–4), 303–316.
- Brönnimann, D., Knipper, C., Pichler, S.L., Röder, B., Rissanen, H., Stopp, B., Rentzel, P., 2018. The lay of land: Strontium isotope variability in the dietary catchment of the Late Iron Age proto-urban settlement of Basel-Gasfabrik, Switzerland. *J. Archaeol. Sci. Rep.* 17, 279–292.
- Bryant, J.D., Froelich, P.N., 1995. A model of oxygen isotope fractionation in body water of large mammals. *Geochim. Cosmochim. Acta* 59 (21), 4523–4537.
- Budd, P., Montgomery, J., Barreiro, B., Thomas, R.G., 2000. Differential diagenesis of strontium in archaeological human dental tissues. *Appl. Geochem.* 15 (5), 687–694.
- Capo, R.C., Stewart, B.W., Chadwick, O.A., 1998. Strontium isotopes as tracers of ecosystem processes: theory and methods. *Geoderma* 82 (1–3), 197–225.
- Carlús, X., Lopez-Cachero, J., Oliva, M., Palomo, A., Rodríguez, A., Terrats, N., Lara, C., Villena, N., 2007. Cabanes, sítges i tombes. El paratge de Can Roqueta (Sabadell, Vallès Occidental) del 1300 al 500 ANE. *Museu d'Història de Sabadell, Sabadell*.
- Casellas, S., Montón, S., Martínez, J. (1999). “Les restes faunístiques de Can Roqueta. Campanyes de 1990 i 1992”. In: González Marcén, P., Martín, A., Mora, R. (ed.) *Can Roqueta. Un establiment pagès prehistòric i medieval (Sabadell, Vallès Occidental)*. Barcelona: Direcció General del Patrimoni Cultural, Servei d'Arqueologia, p. 255–258. (Excavacions arqueològiques a Catalunya; 16).
- Cerling, T.E., Harris, J.M., MacFadden, B.J., Leakey, M.G., Quade, J., Eisenmann, V., Ehleringer, J.R., 1997. Global vegetation change through the Miocene/Pliocene boundary. *Nature* 389 (6647), 153–158.
- Chenery, C.A., Pashley, V., Lamb, A.L., Sloane, H.J., Evans, J.A., 2012. The oxygen isotope relationship between the phosphate and structural carbonate fractions of human bioapatite. *Rapid Communications in Mass Spectrometry* 26 (3), 309–319.
- Chiaradia, M., Gallay, A., Todt, W., 2003. Different contamination styles of prehistoric human teeth at a Swiss necropolis (Sion, Valais) inferred from lead and strontium isotopes. *Appl. Geochem.* 18 (3), 353–370.
- Chillón, B.S., Alberdi, M.T., Leone, G., Bonadonna, F.P., Stenni, B., Longinelli, A., 1994. Oxygen isotopic composition of fossil equid tooth and bone phosphate: an archive of difficult interpretation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 107 (3–4), 317–328.
- Clavel, B., Lepetz, S., Chauvey, L., Schiavinato, S., Tonasso-Calviere, L., et al., 2022. Sex in the city: Uncovering sex-specific management of equine resources from prehistoric times to the Modern Period in France. *J. Archaeol. Sci. Rep.* Vol 41, 103341.
- Comar, C.L., Russell, R.S., Wasserman, R.H., 1957. Strontium-calcium movement from soil to man. *Science* 126 (3272), 485–492.
- Coplen, T.B., 1988. Normalization of oxygen and hydrogen isotope data. *Chem. Geol.: Isotope Geosci. Section* 72 (4), 293–297.
- Crowell-Davis, S.L., Houpt, K.A., Carnevale, J., 1985. Feeding and drinking behavior of mares and foals with free access to pasture and water. *J. Anim. Sci.* 60 (4), 883–889.
- Dansgaard, W., 1964. Stable isotopes in precipitation. *Tellus* 16 (4), 436–468.
- Delgado-Huertas, A., Iacumin, P., Stenni, B., Chillón, B.S., Longinelli, A., 1995. Oxygen isotope variations of phosphate in mammalian bone and tooth enamel. *Geochim. Cosmochim. Acta* 59 (20), 4299–4305.
- Díaz-Zorita Bonilla, M., Knudson, K.J., Escudero Carrillo, J., Bocherens, H., García Sanjuán, L., 2017. Mobility patterns and paleodietary insights into human and cattle at the Copper Age Mega-site of Valencia (Seville, Spain) through  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotope analysis. *MENGA. J. Andalusian Archaeol.* 8, 53–70.
- Díaz-Zorita Bonilla, M., Knudson, K.J., Carrillo, J.E., Bocherens, H., Sanjuán, L.G., 2017. Mobility patterns and paleodietary insights into humans and cattle at the Copper Age Mega-site of Valencia (Seville, Spain) through  $^{18}\text{O}$  and  $^{13}\text{C}$  isotope analyses. *Menga: Revista de prehistoria de Andalucía* 8, 53–68.
- Díaz-Zorita Bonilla, M., Beck, J., Aranda Jiménez, G., Milesi García, L., Sánchez Romero, M., Lozano Medina, A., Escudero Carrillo, J., Knipper, C., 2020. The deposition of human remains inside Chalcolithic ditched enclosures: Ditch 5 at Marroquies (Jaén, Spain). *Eur. J. Archaeol.* 1–26 <https://doi.org/10.1017/ea.2020.4>.
- Dolce, R., 2014. Equids as luxury gifts at the centre of interregional economic dynamics in the archaic urban cultures of the ancient near east. *Syria. Archéologie, art et histoire* 91, 55–75.
- Ehleringer, J.R., Monson, R.K., 1993. Evolutionary and ecological aspects of photosynthetic pathway variation. *Annual Review of Ecology and Systematics* 24 (1), 411–439.
- Evans, J.A., Montgomery, J., Wildman, G., Boulton, N., 2010. Spatial variations in biosphere  $^{87}\text{Sr}/^{86}\text{Sr}$  in Britain. *J. Geol. Soc. London* 167 (1), 1–4.
- Fages, A., Seguin-Orlando, A., Germonpré, M., Orlando, L., 2020. Horse males became over-represented in archaeological assemblages during the Bronze Age. *J. Archaeol. Sci. Rep.* 31, 102364.
- Farquhar, G., 1991. Use of stable isotopes in evaluating plant water use efficiency. *Stable Isotopes in Plant Nutrition, Soil Fertility and Environmental Studies. Proceedings of a Symposium. Vienna, 1–5 October 1990*. International Atomic Energy Agency, Vienna, pp. 475–488.
- Farquhar, G.D., Von Caemmerer, S., 1982. Modelling of photosynthetic response to environmental conditions. *Physiological plant ecology II: water relations and carbon assimilation* 549–587.
- Farquhar, G.D., O'Leary, M.H., Berry, J.A., 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Functional Plant Biology* 9 (2), 121–137.
- Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. *Annu. Rev. Plant Biol.* 40 (1), 503–537.
- Faure, G., Mensing, T.M., 2005. *Isotopes*. John Wiley & Sons Inc, Principles and applications.
- Feranec, R.S., Hadly, E.A., Paytan, A., 2009. Stable isotopes reveal seasonal competition for resources between late Pleistocene bison (*Bison*) and horse (*Equus*) from Rancho La Brea, southern California. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 271 (1–2), 153–160.
- Ferrio, J.P., Arous, J.L., Buxó, R., Voltas, J., Bort, J., 2005. Water management practices and climate in ancient agriculture: inferences from the stable isotope composition of archaeobotanical remains. *Vegetation History and Archaeobotany* 14, 510–517.
- Fox, J. 2007. The car package. *R Foundation for Statistical Computing*.
- Gat, J.R., 1980. The isotopes of hydrogen and oxygen in precipitation. In: *Handbook of environmental isotope geochemistry*. Vol. 1.
- Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Planet. Sci.* 24, 225–262.
- Gómez, X., 2003. Fetos de équido en Els Vilars (Arbeca, Lleida): un nuevo tipo de deposición en el hábitat durante la primera Edad del Hierro en Cataluña, in: Quesada F., Zamora, M. (Eds.), *El caballo en la antigua Iberia. Estudio sobre los équidos en la Edad del Hierro*. Real Academia de la Historia, Colección B. *Archaeologica Hispana*, pp. 209–215.
- Grandal-d'Anglade, A., Albizuri, S., López-Cachero, F.J., 2021. Equine diet during protohistoric times in the Northeast of the Iberian Peninsula: stable isotope data (C, N) from bone collagen. *Data Brief* 38, 107374.
- Grant, A., 1984. Animal husbandry. In: Cunliffe, B. (Ed.), *Danebury: an Iron Age hillfort in Hampshire*. Council for British Archaeology, London, pp. 496–548.
- Harcourt, R., 1979. The animal bones, in: Wainwright, G. (ed.), *Gussage All Saints: an Iron Age settlement in Dorset*. Archaeological Reports 10, Department of the Environment, Her Majesty's Stationery Office, London, pp. 150–160.
- Heaton, T.H.E., 1999. Spatial, species, and temporal variations in the  $^{13}\text{C}/^{12}\text{C}$  ratios of C3 plants: implications for paleodiet studies. *J. Archaeol. Sci.* 26, 637–649.
- Hoppe, K.A., Stover, S.M., Pascoe, J.R., Amundson, R., 2004. Tooth enamel biomineralization in extant horses: implications for isotopic microsampling. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 206 (3–4), 355–365.
- Horton, T.W., Defliese, W.F., Tripati, A.K., Oze, C., 2016. Evaporation induced  $^{18}\text{O}$  and  $^{13}\text{C}$  enrichment in lake systems: a global perspective on hydrologic balance effects. *Quat. Sci. Rev.* 131, 365–379.
- King, S.R.B., 2002. Home range and habitat use of free-ranging Przewalski horses at Hustai National Park, Mongolia. *Appl. Anim. Behav. Sci.* 78 (2–4), 103–113.
- Knockaert, J., Balasse, M., Rendu, C., Burens, A., Campmajo, P., Carozza, L., Vigne, J.D., 2018. Mountain adaptation of caprine herding in the eastern Pyrenees during the Bronze Age: a stable oxygen and carbon isotope analysis of teeth. *Quat. Int.* 484, 60–74.
- Koch, P.L., 1998. Isotopic reconstruction of past continental environments. *Annu. Rev. Earth Planet. Sci.* 26 (1), 573–613.

- Kohn, M.J., Schoeninger, M.J., Valley, J.W., 1996. Herbivore tooth oxygen isotope compositions: effects of diet and physiology. *Geochim. Cosmochim. Acta* 60, 3889–3896.
- Kohn, M.J., Welker, J.M., 2005. On the temperature correlation of  $\delta^{18}\text{O}$  in modern precipitation. *Earth Planet. Sci. Lett.* 231 (1–2), 87–96.
- Kristula, M.A., McDonnell, S.M., 1994. Drinking water temperature affects consumption of water during cold weather in ponies. *Appl. Anim. Behav. Sci.* 41 (3–4), 155–160.
- Krueger, H. W., Sullivan, C. H. (1984). Models for carbon isotope fractionation between diet and bone.
- Lee-Thorp, J.A., Sealy, J.C., Van Der Merwe, N.J., 1989. Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *J. Archaeol. Sci.* 16 (6), 585–599.
- Levin, N.E., Cerling, T.E., Passey, B.H., Harris, J.M., Ehleringer, J.R., 2006. A stable isotope aridity index for terrestrial environments. *Proc. Natl. Acad. Sci. U. S. A.* 103, 11201–11205.
- Lee-Thorp, J., Spoonheimer, M., 2003. Three case studies used to reassess the reliability of fossil bone and enamel isotope signals for paleodietary studies. *J. Anthropol. Archaeol.* 22 (3), 208–216.
- Librado, P., Khan, N., Fages, A., Kusliy, M.A., Suchan, T., Tonasso-Calvière, L., Hansen, S., 2021. The origins and spread of domestic horses from the Western Eurasian steppes. *Nature* 598 (7882), 634–640.
- Lightfoot, E., O'Connell, T.C., 2016. On the use of biomineral oxygen isotope data to identify human migrants in the archaeological record: intra-sample variation, statistical methods and geographical considerations. *PLoS one* 11 (4), e0153850.
- Lightfoot, E., Ustunkaya, M.C., Przelomska, N., O'Connell, T.C., Hunt, H.V., Jones, M.K., Petrie, C.A., 2020. Carbon and nitrogen isotopic variability in foxtail millet (*Setaria italica*) with watering regime. *Rapid Communications in Mass Spectrometry* 34 (6), e8615.
- López Cachero, J., Albizuri, S., Majó, T., Carlús, X., Oliva Poveda, M., Palomo, A., Rodríguez, A., Terrats, N., (in press). Depósitos de caballo en Can Roqueta (Sabadell, Barcelona) durante el Bronce Final y la Primera Edad del Hierro. In: Congreso de Prehistoria y Protohistoria del Mediterráneo Occidental, Museu de Menorca, 27–30 abril 2017.
- Luz, B., Kolodny, Y., Kovach, J., 1984. Oxygen isotope variations in phosphate of biogenic apatites, III. Conodonts. *Earth Planet. Sci. Lett.* 69 (2), 255–262.
- McCrea, J.M., 1950. On the isotopic chemistry of carbonates and a paleotemperature scale. *J. Chem. Phys.* 18 (6), 849–857.
- Madgwick, R., Lewis, J., Grimes, V., Guest, P., 2019. On the hoof: exploring the supply of animals to the Roman legionary fortress at Caerleon using strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotope analysis. *Archaeol. Anthropol. Sci.* 11 (1), 223–235.
- Magny, M., Billaud, Y., Bossuet, G., Gauthier, E., Marguet, A., Mouthon, J., Richard, H., Vanniere, B. (2007). Variations du climat pendant l'âge du Bronze au centre ouest de l'Europe : vers l'établissement d'une chronologie à haute résolution. In: Richard, H., Magny, M., Mordant, C. (Eds.), *Environnements et cultures à l'âge du Bronze en Europe occidentale*. CTHS Editions, pp. 13–28.
- Magny, M., Galop, D., Bellintani, P., Desmet, M., Didier, J., Haas, J.N., Martinelli, N., Pedrotti, A., Scandolari, R., Stock, A., Vanniere, B., 2009. Late-Holocene climatic variability south on the Alps as recorded by lake-level fluctuation at Lake Ledro, Trentino. Italy. *Holocene* 19 (4), 575–589.
- Makarewicz, C.A., Pederzani, S., 2017. Oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) isotopic distinction in sequentially sampled tooth enamel of co-localized wild and domesticated caprines: Complications to establishing seasonality and mobility in herbivores. *Palaeogeography, Palaeoclimatology, Palaeoecology* 485, 1–15.
- Makarewicz, C.A., Winter-Schuh, C., Byerly, H., Houle, J.L., 2018. Isotopic evidence for ceremonial provisioning of Late Bronze age khirigsuurs with horses from diverse geographic locales. *Quat. Int.* 476, 70–81.
- Minniti, C., Valenzuela-Lamas, S., Evans, J., Albarella, U., 2014. Widening the market. Strontium isotope analysis on cattle teeth from Owslebury (Hampshire, UK) highlights changes in livestock supply between the Iron Age and the Roman period. *J. Archaeol. Sci.* 42, 305–314.
- Miró, F., Manso, C., Diz, A., Novales, M., 2020. Maxillary Incisors of the Horse before and at the Beginning of the Teeth Shedding: Radiographic and CT Study. *Animals* 10 (9), 1618.
- Monson, R.K., Edwards, G.E., Ku, M.S., 1984. C3–C4 intermediate photosynthesis in plants. *BioScience* 34 (9), 563–574.
- Navarrete, V., Tornero, C., Balasse, M., Saña, M., 2019. Food management of early introduced caprine and bovine herds in the early Neolithic site of La Draga (Banyoles): an isotopic approach. *Int. J. Osteoarchaeol.* 29 (6), 986–998.
- Nelson, B.K., DeNiro, M.J., Schoeninger, M.J., De Paolo, D.J., Hare, P.E., 1986. Effects of diagenesis on strontium, carbon, nitrogen and oxygen concentration and isotopic composition of bone. *Geochim. Cosmochim. Acta* 50 (9), 1941–1949.
- Nieto-Espinat, A., 2012. Entre el consum i l'afecte. La interacció entre els animals i les comunitats protohistòriques de la plana occidental catalana (segles VII–IV aC). Universitat de Lleida. Doctoral dissertation.
- Nieto-Espinat, A., Gardeisen, A., Junyent, E., López, J.B. (2010). Inhumations de fœtus d'équidés dans la forteresse du premier âge du Fer de Els Vilars (Arbeca Catalogne), in : Gardeisen, A., Furet, E., Boulbes, N. (Eds.), *Histoire d'équidés, des textes, des images et des os*, Monographies d'Archéologie Médiérranéenne, Hors série; 4, Lattes, pp. 125–148.
- Ogutu, J.O., Piepho, H.P., Reid, R.S., Rainy, M.E., Kruska, R.L., Worden, J.S., Nyabenge, M., Hobbs, N.T., 2010. Large herbivore responses to water and settlements in savannas. *Ecol. Monogr.* 80 (2), 241–266.
- O'Leary, M.H., 1988. Carbon isotopes in photosynthesis. *BioScience* 38 (5), 328–336.
- Palomo, A., Terrats, N., Oliva, M., Rodríguez, A., Majó, T., 2016. El complex arqueològic de Can Roqueta: un poblat paradigmàtic del bronze inicial a la Depressió Prelitoral Catalana. *Arraona: revista d'història* 58–77.
- Passey, B.H., Cerling, T.E., Perkins, M.E., Voorhies, M.R., Harris, J.M., Tucker, S.T., 2002. Environmental change in the Great Plains: an isotopic record from fossil horses. *The Journal of Geology* 110 (2), 123–140.
- Pederzani, S., Britton, K., 2019. Oxygen isotopes in bioarchaeology: Principles and applications, challenges and opportunities. *Earth Sci. Rev.* 188, 77–107.
- Pin, C., Briot, D., Bassin, C., Poitrasson, F., 1994. Concomitant separation of strontium and samarium-neodymium for isotopic analysis in silicate samples, based on specific extraction chromatography. *Analytica Chimica Acta* 298 (2), 209–217.
- Piña, A., Saña, M. (2004). Informe de l'anàlisi arqueozoològica dels conjunts de restes de fauna recuperats al jaciment de Can Roqueta / Torre-romeu (Sabadell, Vallès Occidental). In: Oliva, M., Terrats, N. *El jaciment arqueològic de Can Roqueta / Torre Romeu (Sabadell, Vallès Occidental)*. Campanya 2002–2003. Barcelona: Departament de Cultura, Servei d'Arqueologia: Generalitat de Catalunya. Faunal report.
- Price, T.D., Burton, J.H., Bentley, R.A., 2002. The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry* 44 (1), 117–135.
- Pyankov, V.I., Ziegler, H., Akhiani, H., Deigele, C., Luettge, U., 2010. European plants with C4 photosynthesis: geographical and taxonomic distribution and relations to climate parameters. *Bot. J. Linn. Soc.* 163 (3), 283–304.
- Quade, J., Cerling, T.E., 1995. Expansion of C4 grasses in the late Miocene of northern Pakistan: evidence from stable isotopes in paleosols. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 115 (1–4), 91–116.
- Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Talamo, S., 2020. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radiocarbon* 62 (4), 725–757.
- Riera-Mora, S., Esteban-Amat, A., 1994. Vegetation history and human activity during the last 6000 years on the central Catalan coast (northeastern Iberian Peninsula). *Veg. Hist. Archaeobotany* 3 (1), 7–23.
- Roche, D., Ségalen, L., Senut, B., Pickford, M., 2013. Stable isotope analyses of tooth enamel carbonate of large herbivores from the Tugen Hills deposits: palaeoenvironmental context of the earliest Kenyan hominids. *Earth Planet. Sci. Lett.* 381, 39–51.
- Rovira, M. C., & López-Cachero, J. (2016). Las fíbulas serpentiniformes de Cataluña en el marco del Mediterráneo noroccidental. In *Vie quotidienne, tombes et symboles des sociétés protohistoriques de Méditerranée nord-occidentale: mélanges offerts à Bernard Dedet* (pp. 705–719). Éditions de l'Association pour le Développement de l'Archéologie en Languedoc-Roussillon.
- Rovira, M. C., Hunt Ortiz, M. A., Montero Ruiz, I., Rovira Llorens, S., López Cachero, F. J. (2008). Caracterización elemental e isotópica de bronce de la necrópolis protohistórica Can Piteu-Can Roqueta (Sabadell, Barcelona). In: Rovira Llorens, S., García Heras, M., Gener Moret, M., Montero Ruiz, I. (2008). *Actas del VII Congreso Ibérico de Arqueometría* (Madrid, 8–10 octubre 2007), pp. 448–457.
- Rozanski, K., Araguás-Araguás, L., Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. *American Geophysical Union*.
- Sarkar, D., Sarkar, M.D., KernSmooth, S., 2015. Package 'lattice'. Version (20), 33.
- Slowikowski, K., Schep, A., Hughes, S., Lukauskas, S., Irission, J. O., Kamvar, Z. N., ... & Slowikowski, M. K. (2018). Package ggrepel. *Automatically position non-overlapping text labels with 'ggplot2'*.
- Smedley, M.P., Dawson, T.E., Comstock, J.P., Donovan, L.A., Sherrill Dem Cook, C.S., Ehleringer, J.R., 1991. Seasonal carbon isotope discrimination in a grassland community. *Oecologia* 85, 314–320.
- Smith, B.N., Epstein, S., 1971. Two categories of  $^{13}\text{C}/^{12}\text{C}$  ratios for higher plants. *Plant Physiol.* 47 (3), 380–384.
- Stacy, E.M., 2008. Stable Isotopic Analysis of Equid (Horse) Teeth from Mongolia. University of Pittsburgh (Doctoral dissertation).
- Sullivan, C.H., Krueger, H.W., 1981. Carbon isotope analysis of separate chemical phases in modern and fossil bone. *Nature* 292 (5821), 333–335.
- Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotope ratios in primary lacustrine carbonates. *Chemical Geol. Isotope Geosci. Section* 80 (4), 261–279.
- Tieszen, L.L., 1991. Natural variations in the carbon isotope values of plants: Implications for archaeology, ecology, and paleoecology. *J. Archaeol. Sci.* 18, 227–248.
- Tieszen, L.L., Fagre, T., 1993. Carbon isotopic variability in modern and archaeological maize. *J. Archaeol. Sci.* 20 (1), 25–40.
- Tipple, B.J., Pagani, M., 2007. The early origins of terrestrial C4 photosynthesis. *Annu. Rev. Earth Planet. Sci.* 35, 435–461.
- Toots, H., Voorhies, M.R., 1965. Strontium in fossil bones and the reconstruction of food chains. *Science* 149 (3686), 854–855.
- Valenzuela-Lamas, S., Jiménez-Manchón, S., Evans, J., López, D., Jorner, R., Albarella, U., 2016. Analysis of seasonal mobility of sheep in Iron Age Catalonia (north-eastern Spain) based on strontium and oxygen isotope analysis from tooth enamel: first results. *J. Archaeol. Sci. Rep.* 6, 828–836.
- Valenzuela-Lamas, S., Orengo, H.A., Bosch, D., Pellegrini, M., Halstead, P., Nieto-Espinat, A., Jorner-Niella, R., 2018. Shipping amphorae and shipping sheep? Livestock mobility in the north-east Iberian Peninsula during the Iron Age based on strontium isotopic analyses of sheep and goat tooth enamel. *PLoS One* 13 (10), e0205283.
- van Dam, J.A., Reichart, G.J., 2009. Oxygen and carbon isotope signatures in late Neogene horse teeth from Spain and application as temperature and seasonality proxies. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 274 (1–2), 64–81.
- van Geel, B., Buurman, J., Waterbolk, H.T., 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. *J. Quaternary Sci. Published for the Quaternary Res. Association* 11 (6), 451–460.
- Varro, *De re rustica*.

- Van der Merwe, N.J., Medina, E., 1991. The canopy effect, carbon isotope ratios and foodwebs in Amazonia. *J. Archaeol. Sci.* 18 (3), 249–259.
- Viner, S., Evans, J., Albarella, U., & Pearson, M. P. (2010). Cattle mobility in prehistoric Britain: strontium isotope analysis of cattle teeth from Durrington Walls (Wiltshire, Britain). *Journal of Archaeological Science*, 37(11), 2812–2820.
- Wallace, M., Jones, G., Charles, M., Fraser, R., Halstead, P., Heaton, T.H., Bogaard, A., 2013. Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. *World Archaeology* 45 (3), 388–409.
- Wickham, H., 2011. ggplot2. *Wiley Interdiscip. Rev. Comput. Stat.* 3 (2), 180–185.
- Wickham, H., Bryan, J., Kalicinski, M., Valery, K., Leitiene, C., Colbert, B., ... & Bryan, M. J. (2019). Package 'readxl'.
- Willmes, M., Bataille, C.P., James, H.F., Moffat, I., McMorrow, L., Kinsley, L., Grün, R., 2018. Mapping of bioavailable strontium isotope ratios in France for archaeological provenance studies. *Appl. Geochem.* 90, 75–86.
- Zazzo, A., Mariotti, A., Lécuyer, C., Heintz, E., 2002. Intra-tooth isotope variations in late Miocene bovid enamel from Afghanistan: paleobiological, taphonomic, and climatic implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 186 (1–2), 145–161.

### Further Reading

- Guede, I., Ortega, L.A., Zuluaga, M.C., Alonso-Olazabal, A., Murelaga, X., Pina, M., Iacumin, P., 2017. Isotope analyses to explore diet and mobility in a medieval Muslim population at Tauste (NE Spain). *PLoS One* 12 (5), e0176572.
- Lepetz, S., Clavel, B., Alioğlu, D., Chauvey, L., Schiavinato, S., Tonasso-Calvière, L., Orlando, L., 2021. Historical management of equine resources in France from the Iron Age to the Modern Period. *J. Archaeol. Sci. Rep.* 40, 103250.
- Pellegrini, M., Snoeck, C., 2016. Comparing bioapatite carbonate pre-treatments for isotopic measurements: Part 2—Impact on carbon and oxygen isotope compositions. *Chem. Geol.* 420, 88–96.