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Citation for final published version:

Guillamon-Davila, Antonio, Martinez Sanchez, Rafael, Nederbragt, Alexandra, Andersen, Morten and Madgwick, Richard 2024. Tracing the path: First attempt of a multi-isotope approach to animal management in the Late Roman city of Torreparedones (Baena, Spain). *Journal of Archaeological Science: Reports* 60 , 104851. 10.1016/j.jasrep.2024.104851

Publishers page: <https://doi.org/10.1016/j.jasrep.2024.104851>

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Highlights

- This work is the first attempt at a multi-isotopic study of Roman cattle remains from the south of the Iberian Peninsula, dated between the 3rd and 4th centuries CE.
- The taxa analysed belong to the main livestock species of the site.
- The results indicate free-range husbandry in an open landscape for all livestock analysed.
- Cattle and caprine have shown different mobility management strategies.
- This study aims to help develop the stable isotope analysis of the southern Iberian Peninsula during Roman times.

Abstract

During the 3rd century CE, the city of Torreparedones, in the province of Baetica, experienced a change in its social, urban and economic paradigm. To understand the complexity of the husbandry activities in the southern region of Roman Hispania during this period of change, a multi-isotope analysis has been undertaken. This analysis has included $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in 15 animals combining bone collagen and tooth enamel samples. Four plant samples were also taken for the characterization of the local bioavailable Sr. The results suggest a great variety of management regimes in the four main taxa used in the site. Differences have been detected in the feeding of animals from the same species not only in the kind of graze consumed but also in seasonal access to food and water. The analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ has allowed local Sr bioavailability to be established and also to determine the likely local origins of 9 of the 15 animals. The use of predictive models suggests potential origins of some animals up to hundreds of kilometres away, pointing to wide-ranging trade routes worthy of exploration in future research

1. Introduction

1.1. Roman zooarchaeology in Roman Hispania

The expansion of the Roman Empire brought extraordinary human demographic growth. This was related to changes in agricultural and livestock management practices linked to the growing demand for food, not only from the population but also from the war machine behind the military conquests ([Valenzuela-Lamas and Albarella, 2017](#); [Guest et al., 2023](#)). This expansion also brought with it new possibilities for trade and connectivity, thanks to a single administration which controlled a vast territory, leading to unprecedented human and animal mobility.

In this context, farming and animal husbandry research is a key part of the study of the economic development of the Roman state. However, the multidisciplinary integration of this area of archaeology in the Ancient World is very recent ([Guest et al., 2023](#)). In the past, the economic development of Roman Hispania has been approached principally from classical sources. Other authors have pointed to the need to extend archaeological studies beyond material culture for the estimation of population density and occupation of the land ([Ariño Gil and Díaz, 1999](#)). The lack of attention that zooarchaeological material has received, especially in historical periods such as Roman times, has been highlighted for over 40 years ([Altuna, 1980](#)).

Both in southern Spain and Portugal, the number of studies, focusing on the husbandry of the Roman Empire has grown significantly over the last 20 years. This has allowed the detection of numerous changes in livestock management related to the growing need to supply a population dependent on agricultural production. ([Albarella et al., 2008](#); [Colominas Barberà, 2017](#); [Detry et al., 2022](#); [Valenzuela-Lamas and Albarella, 2017](#)). This change is closely related to an increase in meat production, as well as to the need to ensure an efficient labour force that allows for the optimal exploitation of agricultural production.

This paper presents results from the first isotope project to examine livestock management in southern Roman Hispania. It is also the first to extend beyond a focus on the human diet. For this purpose, multi-isotope analyses have been carried out including $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in bone collagen samples, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in sequential enamel samples and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in enamel samples. These analyses aim to provide new insights into the management, seasonal mobility and grazing routes employed in the Middle Guadalquivir Basin.

The analysis of plant samples from pristine landscapes ([following Holt et al., 2021](#)) surrounding the site has been used to characterise locally bioavailable strontium, adding data for a geographical area with relatively little research of this type.

Finally, the interpretations will allow us to broaden our knowledge of the economy of Torreparedones, a late Roman city immersed in a context of social, economic and demographic crisis.

1.2. Isotope analysis applied to Roman zooarchaeology

The increase in studies focussed on this period has not only been in number but also the precision of the interpretations and the range of analytical techniques ([Madgwick et al., 2019](#); [Messana et al., 2023](#); [Salazar-García et al., 2023](#); [Trentacoste et al., 2023](#)). Among these techniques, isotope analysis has the greatest potential for examining the management of fauna.

The $\delta^{13}\text{C}$ analysis is useful in discerning between the type of plants consumed by herbivores and omnivores, based on different photosynthetic pathways, and the stable isotope fractionation in

the food chain (De Niro and Epstein, 1978; Deines, 1980; Boutton, 1991, Minagawa and Wada, 1984). There are also environmental factors that can affect the ratio of stable carbon isotopes. In particular, the canopy effect tends to cause a significant difference in $\delta^{13}\text{C}$ between closed forest ecosystems, rich in tree species, and open ecosystems, dominated by herbaceous species, due to the increase in $\delta^{13}\text{C}$ from the base of the trees to the treetops (Goude, 2016).

The analysis of $\delta^{15}\text{N}$ is more closely related to the trophic level at which an individual feeds, allowing consumers to be positioned in a food network (Boutton, 1991). It is also important to highlight that the difference in nitrogen cycles and the greater extension of the food webs in marine environments, generate different isotope values, with higher $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ than terrestrial C3 ecosystems. The analysis of bone collagen provides a long-term average of the protein part of the diet due to bone remodelling, whereas the analysis of dentine, which undergoes very little remodelling, provides a more temporally resolved dietary signal (Katzenberg, 2011).

The analysis of radiogenic strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotope ratios is one of the main techniques used in both animal and human mobility studies. Strontium in underlying geology weathers into sediments and enters the food chain, ultimately manifesting in bones and teeth that are recovered archaeologically (Bentley, 2005). Once bioavailable strontium is ascertained (in this study, through the analysis of modern plants), individuals that are consistent with being locally and non-locally raised can be identified.

Dental enamel is targeted for analysis. This is due not only to its compositional stability and resistance to diagenetic alteration after its formation, but also as it can provide a temporally resolved indication of origins, rather than a longer-term average that has the potential to mix signals from different locations (Holt et al., 2021).

The analysis of $\delta^{18}\text{O}$ isotopes has become increasingly widespread in zooarchaeology. The $\delta^{18}\text{O}$ in the organism is closely linked to water consumption. Factors such as temperature, the source of evaporated water, and the amount and timing of precipitation or dry forage intake, affect the stable oxygen isotope ratio (Dansgaard, 1964; Gat, 1980; Makarewicz and Pederzani, 2017). However, the relevance of the technique is often based on the variation of stable oxygen isotopes at different altitudes. This is because, at mid and high latitudes, the stable oxygen isotope composition of meteoric water varies seasonally, with higher $\delta^{18}\text{O}$ values in the warm months and lower values in the cold months (Dansgaard, 1964; Gat, 1980). Based on these data, the ratio of stable oxygen isotopes can be used to infer the altitude at which water was ingested at a particular time of the tooth's formation (Longinelli, 1984; Luz et al., 1984; Kohn, 1996; Kohn et al., 1996; Lacumin and Longinelli, 2002). Considering that hypsodont taxa present a linear sequence of development from crown to root apex, serial sampling can provide data on transhumance practices carried out in these animals (Valenzuela-Lamas, 2020).

These analyses allow us to gain new insights into animal management in the Roman period, such as feeding, the contribution of marine elements in the diet, seasonality and mobility of livestock through the territory. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ have been commonly analysed in studies of Roman Hispania, although faunal baselines have invariably been used, these studies combine the analysis of faunal samples with human samples to understand human diets (García-Moreno et al., 2022, 2024; Salazar-García et al., 2023). Therefore, the novelty of this study makes it difficult to establish expected results due to the lack of work with which to compare. However, based on the territory surrounding the site and the known feeding pattern of the livestock analysed in this work, it is reasonable to assume that the analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in the bone collagen of

herbivorous would indicate a consumption of C3 plants in an open landscape. These values could be also expected for pigs if the management of these animals match a free-range extensive husbandry. The vegetation present in the thermomediterranean system and the palynological studies carried out on the site support this hypothesis (Carrión García et al., 2022; Rivas Martínez & Gandullo, 1987).

1.3. The Roman site of Torreparedones

The site chosen for this study is the Ibero-Roman site of Torreparedones, also known as Cerro de las Vírgenes or Castro el Viejo. It is located between the towns of Baena and Castro del Río (Cordoba, Spain), in the heart of the Andalusian countryside (WGS-84: 37.75424301415889, -4.376831034987846). In the present day, barely 10% of the 11 ha site has been excavated, which is surprising considering the large number of architectural elements discovered (Figure 1).

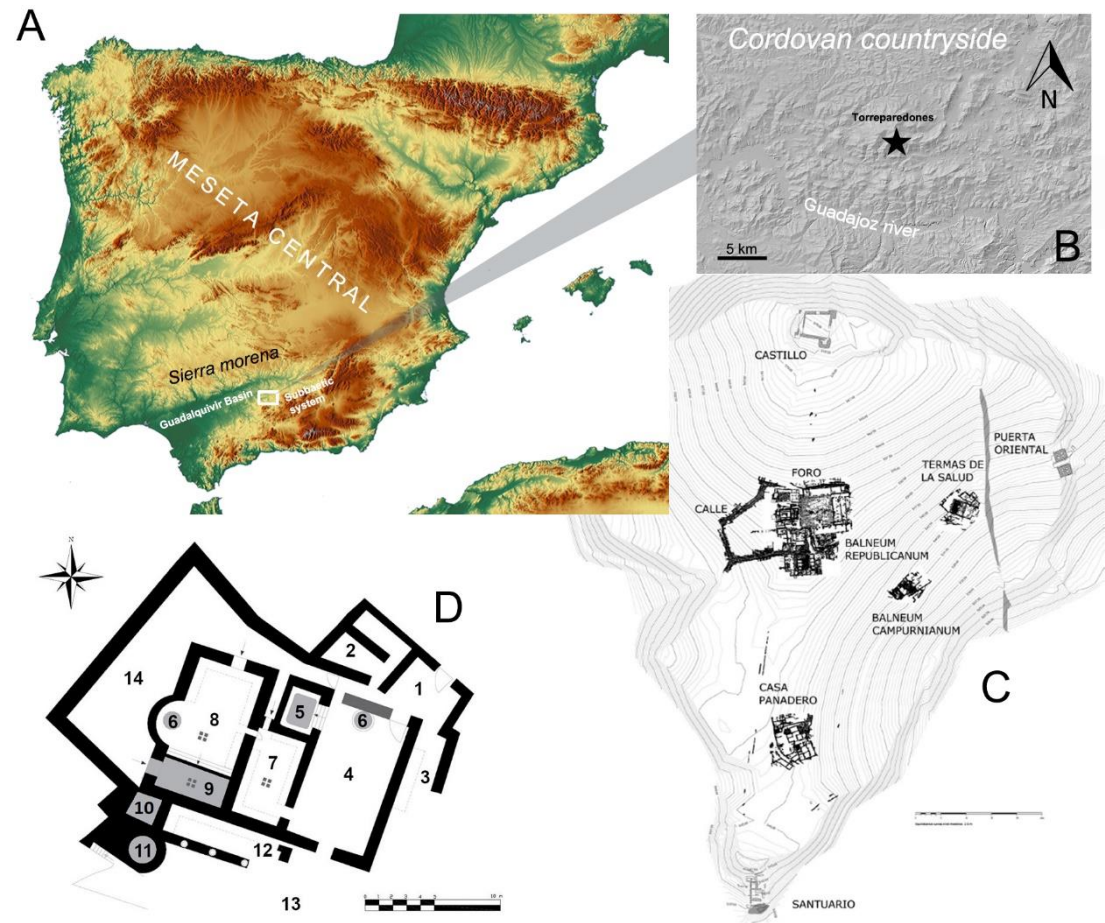


Figure 1. Left top, location of Torreparedones. Right, map of the site. Left bottom planimetry of the Easter Baths: E1; Hall, E2: Unctorium/Districtarium, E3: Latrines, E4: Apodyterium/Frigidarium, E5: Pool, E6: Labrum, E7: Tepidarium, E8: Caldarium, E9: Alveus, E10: Cistern, E11: Well, E12: Valetudinarium/Ara, E13: Palaestra, E14: Service area.

The site's urban and demographic peak was reached in the Ibero-Roman period. It was during this period that have been recorded several phases of abandonment of public buildings related to the Crisis of the 3rd century CE (Morena López et al., 2012; Ventura Villanueva et al., 2020). In the same context was the abandonment of the Eastern Baths, which were looted and converted into an intramural rubbish dump. The faunal remains analysed in this study come from this context, which was active between the middle 3rd and 5th centuries CE (Ventura Villanueva et al., 2020).

2. Materials and methods

2.1. Selection and preparation of samples

A total of 15 animals were selected for isotope analysis (Table 1). The elements selected were mandibles from individuals whose M3 had already erupted and which, in addition, preserved both the M2 and the M3. For a better understanding of the life and the use of the animals sampled, their age of death has been stated through dental wear (Bovids: Grant, 1982; Jones y Sadler (2012); caprine: Payne, 1973; pigs: Lemoine et al., 2014; dogs: Arnall, 1961). These samples were targeted to maximise information on diet, mobility and seasonality across the growing period of each animal, rather than acquiring limited information on a larger set of animals.

Sample	Taxon	Age of death	U.E.	Room	Site	Period
TP-1	<i>Bos taurus</i>	7-10 years	199	E14	TP Easter Baths	Late Antique
TP-2	<i>Capra hircus</i>	4-6 years	300	E10	TP Easter Baths	Late Antique
TP-3	<i>Ovis aries</i>	4-6 years	8	E2	TP Easter Baths	Late Antique
TP-4	<i>Canis familiaris</i>	Adult	134	E3	TP Easter Baths	Late Antique
TP-5	<i>Capra hircus</i>	2-4 years	134	E3	TP Easter Baths	Late Antique
TP-6	<i>Bos taurus</i>	3-4 years	134	E3	TP Easter Baths	Late Antique
TP-7	<i>Ovis aries</i>	2-3 years	T1	E13	TP Easter Baths	Late Antique
TP-8	<i>Sus domesticus</i>	18-30 months	249	E11	TP Easter Baths	Late Antique
TP-9	<i>Canis familiaris</i>	Adult	397	E3	TP Easter Baths	Late Antique
TP-10	<i>Canis familiaris</i>	Adult	397	E3	TP Easter Baths	Late Antique
TP-11	<i>Sus domesticus</i>	>8 years	37	E2	TP Easter Baths	Late Antique
TP-12	<i>Sus domesticus</i>	12-16 months	30	E3	TP Easter Baths	Late Antique
TP-13	<i>Sus domesticus</i>	12-16 months	249	E11	TP Easter Baths	Late Antique
TP-14	<i>Bos taurus</i>	7-12 years	T1	E13	TP Easter Baths	Late Antique
TP-15	<i>Bos taurus</i>	7-8 years	194	E3	TP Easter Baths	Late Antique

Table 1. Animal samples analysed in this study.

The selected taxa represent the four main livestock species present in the site (cattle, goats, sheep and pigs), as well as the fifth most abundant domestic animal, the dog (Table 2). The analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ was performed in bone collagen and the analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio performed in tooth enamel was done in all the taxa, while the analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ was done only in cattle and caprine due to their hypsodont dentition.

Taxon	NISP	NISP%	Average age at death
<i>Bos taurus</i>	2094	50.81	7,5 years
Caprinae indet.	470	11.4	3 years
<i>Capra hircus</i>	67	1.63	3 years
<i>Ovis aries</i>	95	2.31	3 years
<i>Sus domesticus</i>	796	19.32	8-12 months
<i>Canis familiaris</i>	366	8.88	Adult

Table 2. Number of identify specimens (NISP) of each taxon studied in this work, percentage of the total NISP and approximate average age of death of every taxon.

In addition, four plant samples were taken from biodiversity patches located in the area surrounding the site (Figure 2) to characterise the bioavailable Sr of the local landscapes (Table 3). Priority was given to the collection of fresh herbaceous plants (Poaceae) from relic or fossil (still preserved) landscapes, avoiding modern agricultural zones, industry and roads (following Holt et al., 2021).

Sample	East	North	Lithology	Period	$^{87}\text{Sr}/^{86}\text{Sr}$	uncertainty (± 2 SE%)
TP-16	37.77383	-4.36507	Turbidite formation	Miocene (Lower Serravalian)	0.7088	6.28E-06
TP-17	37.73651	-4.36690	Olitostromic unit	Miocene (Upper Langhian)	0.7083	7.82E-06
TP-18	37.66439	-4.37736	Clay, sandstone and gypsum	Triassic	0.7081	7.48E-06
TP-19	37.66847	-4.38895	Hillside landslides	Quaternary	0.7082	8.74E-06

Table 3. Location, geology and results of isotope analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the plant samples. UTM coordinates Datum ETRS89 30S

For the analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, bone fragments (c. 500mg) were cut from the samples using a Dremel precision drill with a diamond wheel attachment and the surfaces were abraded with a diamond burr to remove adhering contaminants and approximately 10 μm of the cortex. The samples were demineralised in 0.5 M HCl and stored at 4°C. The HCl was changed twice weekly until complete demineralisation (approximately 1 week). The samples were then rinsed with deionised water and gelatinised in pH3 solution (acidified with HCl) in a hot block at 70 °C for 48 hours. They were then filtered using EzeetM filters (8 μm Ezeet-filter, Elkay, Basingstoke), transferred to polypropylene test tubes and frozen overnight before being freeze-dried and weighed.

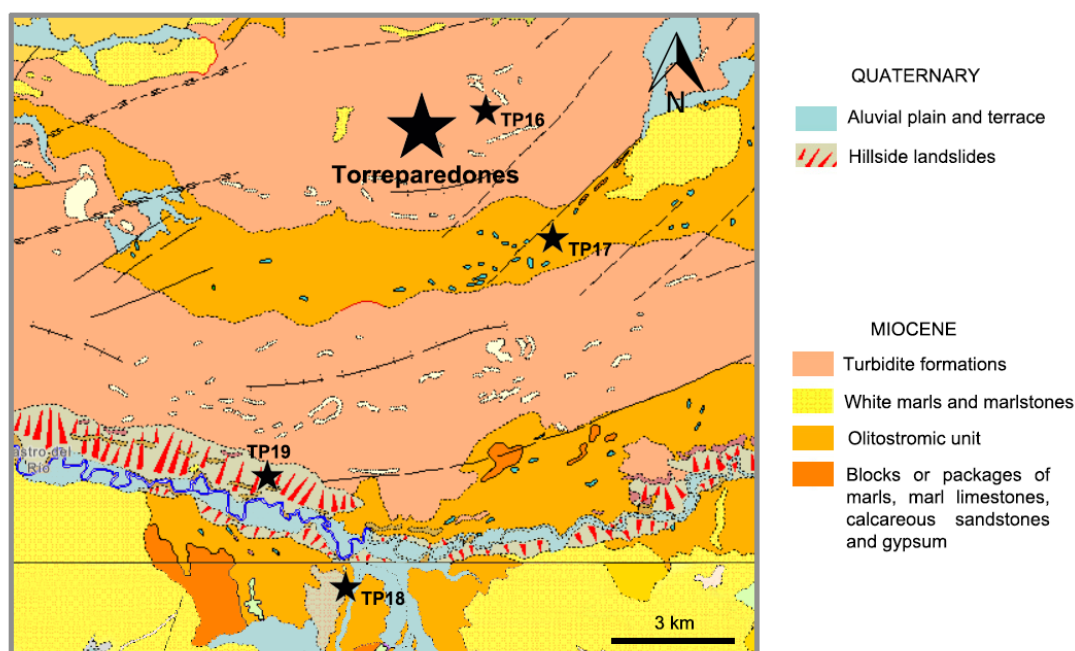


Figure 2. Geological map of the surroundings of the site and location of the plant samples taken. Samples TP-16, TP-17, TP-18, and TP-19. Graphic source: MAGNA 50 map, Spanish Government (public domain).

Stable carbon and nitrogen isotope analysis was undertaken using continuous flow isotope ratio mass spectrometry (CF-IRMS) at Cardiff University Stable Isotope Facility using a Flash 1105 elemental analyser coupled to a ThermoFinnigan Delta V Advantage. The long-term analytical precision (one standard deviation) of the gelatine and caffeine standards was ± 0.08 and ± 0.05 for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$.

For $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio analyses, enamel samples (c. 20 mg) were taken using a Strong 209 precision drill with diamond wheel attachment and all surfaces were abraded with a diamond bur to remove all dentine and adhering contaminants. The enamel samples were taken in different sections on the tooth based on taxon and material preservation criteria. For cattle, the four samples were taken from the buccal side of the mesial lobe. The samples were taken at an average of 9 mm from the root of the M2 and the section of the samples was about 4.8 mm in width. For caprines, the four samples were taken from the buccal side of the mesial lobe. The samples were taken at an average of 10 mm from the root of the M2 and the sections of the samples were about 4 mm wide. For pigs, the three samples from the lower M2 were taken from the lingual side of the mesial lobe. In the case of the upper M2 from TP-11, the advanced state of wear necessitated sampling of the distal cuspid of the buccal side. The samples were taken at an average of 4 mm from the root of the M2 and the sections of the samples were approximately 4 mm wide. Finally, for dogs, the extremely thin enamel of their teeth made sampling more challenging. For TP-9, the sample was taken from the lingual side of the M1, for TP-4, both sides of the M1 were sampled and for TP-10, the small side of its M1 made necessary to sample the canine. According to the tooth eruption ages proposed by Arnall (1961), the eruption timing for these teeth is almost identical, hence no substantial difference is expected for our samples. Each enamel fragment was then cleaned in an ultrasonic bath, rinsed, and dried. A clean enamel fragment weighing a minimum of 16.0 mg was stored in a microcentrifuge tube and transferred to a clean working area (class 100, laminar flow) for further sample preparation and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio analysis at Cardiff Earth Laboratory for Trace Element and Isotope analyses.

The plant samples were first dried in a microwave oven at 300 W power for 10-second intervals to remove as much water as possible and to preserve it up to the laboratory. There, they were frozen and freeze-dried to eliminate all their water content and finally mechanically homogenised before chemical treatment.

The chemical preparation of the samples was carried out at the Trace Element and Isotope Facility (CELTIC) of the School of Earth and Environmental Sciences at Cardiff University. Samples were digested in 8M HNO_3 and heated overnight at 120°C. Strontium extraction used Sr Spec™ resin following a revised version of the protocol of Font et al. (2007). Samples were loaded into resin columns in 1 ml 8M HNO_3 . Matrix elements (including calcium and traces of rubidium) were then eluted in several washes of 8M HNO_3 before the sample was collected in 0.05M HNO_3 and the samples were placed on a hotplate (120°C) overnight. This process was then repeated for a second pass to remove all remaining calcium. Once purified samples were dry, samples were re-dissolved in 0.03M HNO_3 . Strontium isotope ratios were measured using a Nu Instruments Multi-Collector Inductively Coupled Plasma mass spectrometer (MC-ICP-MS) at Cardiff University. All data were first corrected for on-peak blank intensities, then mass bias corrected using the exponential law and a normalization ratio of 8.375209 for $^{88}\text{Sr}/^{86}\text{Sr}$ (Nier, 1938). Residual krypton (Kr) and rubidium (^{87}Rb) interferences were monitored and corrected for using ^{84}Kr and ^{86}Kr ($^{83}\text{Kr}/^{84}\text{Kr} = 0.20175$ and $^{83}\text{Kr}/^{86}\text{Kr} = 0.66474$; without normalization) and ^{85}Rb ($^{85}\text{Rb}/^{87}\text{Rb} = 2.5926$), respectively. Data are also corrected against a NIST SRM 987 value of 0.710246 (Avanzinelli et al., 2005). Accuracy of the method was assessed by measurement of the EC-5 Fossil coral standard during the analytical sessions, which gave an $^{87}\text{Sr}/^{86}\text{Sr}$ average value of 0.709161 ± 0.000039 (2σ , $n=5$), consistent with the approximate value of sea water (0.709180). Total procedural blanks were less than 180pg of Sr, which is negligible relative to the amount of Sr in each sample.

A total of 6 M3s were sampled for sequential analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ on tooth enamel. These pieces corresponded to 3 cattle, 2 sheep and 1 goat. The tooth surface was cleaned by abrasion with a bur. Then, a 3 mm diamond abrasion drill was changed for sequential sampling of tooth enamel. Sampling was performed on the distal lobe of the M3, prioritising the buccal surface whenever possible. All samples were taken progressively at intervals of 2-5 mm from the apex to the enamel-root junction. A total of 48 enamel powder samples (>2.7 mg) were taken.

The stable oxygen and carbon isotope composition of the structural carbonate within the enamel was measured ($\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{carb}}$), with a minimum of 20% of samples subject to replicate analysis (Mean SD $\delta^{13}\text{C}$ = 0.002; Mean SD $\delta^{18}\text{O}$ = 0.014). At the Cardiff University Stable Isotope Facility, samples were acidified for 5 minutes with >100% ortho-phosphoric acid at 70°C and analysed using a Thermo MAT253 dual inlet mass spectrometer coupled to a Kiel IV carbonate preparation device. One in three samples was run in duplicate. The resultant isotope values are reported as per mil ($^{18}\text{O}/^{16}\text{O}$) normalized to the VPDB scale using an in-house carbonate reference material (BCT63) calibrated against NBS19 certified reference material. The long-term reproducibility for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ BCT63 is ± 0.03 per mil (1σ). Oxygen carbonate values ($\delta^{18}\text{O}_{\text{C VPDB}}$) were converted to phosphate ($\delta^{18}\text{O}_{\text{P VSMOW}}$) using the formula from Chenery et al. (2012).

All of the skeletal remains analysed come from domestic deposits from different rooms of the Easter Baths during their use as a rubbish dump. This phase of dumping dates from the first half of the 3rd century to the mid-5th century CE. The ceramic typology and some numismatic finds (Diocletian's coinage) point to the end of the 3rd century and the beginning of the 4th century CE for the definitive landfill. In addition, radiocarbon dating of a burned olive seed, located in E.U. 134 resulted in an estimated date between the 3rd century CE and 4th century CE (Beta-449406, 1790 ± 30 BP), with a calibrated average of c. 290 cal CE (Ventura Villanueva, 2017). The total of the selected elements and the stratigraphic unit to which they belong can be observed in Table 1.

3. Results

3.1. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

The results of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are presented in Table 4 and Figure 3.

Samples	Taxon	Element	$\delta^{15}\text{N}$ mean	$\delta^{13}\text{C}$	%N	%C	C:N
TP-1	<i>Bos taurus</i>	Mandible	6.7	-20.3	6.4	18.4	3.4
TP-6	<i>Bos taurus</i>	Mandible	6.1	-19.7	15.4	43.3	3.3
TP-14	<i>Bos taurus</i>	Mandible	5.7	-20.2	10.8	30.3	3.3
TP-15	<i>Bos taurus</i>	Mandible	6.5	-20.4	5.6	15.4	3.2
TP-2	<i>Capra hircus</i>	Mandible	7.2	-20.2	12.5	35.1	3.3
TP-5	<i>Capra hircus</i>	Mandible	7.0	-18.8	6.2	17.8	3.4
TP-3	<i>Ovis aries</i>	Mandible	6.3	-20.7	14.7	41.1	3.3
TP-7	<i>Ovis aries</i>	Mandible	4.9	-20.0	9.6	26.5	3.3
TP-8	<i>Sus domesticus</i>	Mandible	7.4	-19.8	15.7	44.5	3.3
TP-11	<i>Sus domesticus</i>	Maxilla	4.2	-20.8	15.2	42.2	3.2
TP-12	<i>Sus domesticus</i>	Mandible	6.7	-20.6	8.9	25.0	3.3
TP-13	<i>Sus domesticus</i>	Mandible	6.5	-21.0	13.1	38.3	3.4
TP-4	<i>Canis familiaris</i>	Mandible	9.6	-19.2	13.7	38.8	3.3

TP-9	<i>Canis familiaris</i>	Mandible	9.7	-19.2	15.6	42.6	3.2
TP-10	<i>Canis familiaris</i>	Mandible	9.6	-18.4	13.5	38.3	3.3

Table 4. Results of the analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. Each value represents the mean of duplicate analyses, except TP-15, for which sufficient collagen for only single analysis was preserved.

Cattle have a range of $\delta^{13}\text{C}$ (Mean = -20.1‰ ; SD = 0.32) and $\delta^{15}\text{N}$ (Mean = 6.3‰ ; SD = 0.44) expected for the taxon's feeding type. This indicates a typical herbivorous diet based on C3 plant consumption in an open landscape, consistent with the geographic location of the site.

Goats give similar results for both $\delta^{13}\text{C}$ (Mean = -20.3‰ ; SD = 0.43) and $\delta^{15}\text{N}$ (Mean = 6.3‰ ; SD = 1.05). Although the values are generally consistent with herbivores eating C3 plants in open landscapes, the $\delta^{13}\text{C}$ value for one of the goats (TP-5, -18.8‰) indicates consumption of some C4 plants. Concerning species differences, the values for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in goats are slightly higher (Mean $\delta^{13}\text{C}$ *C. hircus* = -19.5‰ ; Mean $\delta^{13}\text{C}$ *O. aries* = -20.3‰ ; Mean $\delta^{15}\text{N}$ *C. hircus* = 7.1‰ ; Mean $\delta^{15}\text{N}$ *O. aries* = 5.5‰) but this data are not conclusive of any pattern in such a small dataset. Goats show a wider range in both proxies, reflecting the capacity to consume a more diverse range of plants.

The pigs have a similar range of $\delta^{13}\text{C}$ values as the herbivorous taxa (Mean = -20.5‰ ; SD = 0.52). The range of $\delta^{15}\text{N}$ is also similar to the rest of the livestock (Mean = 6.2‰ ; SD = 0.52). TP-11 stands out due to its low $\delta^{15}\text{N}$ value (4.2‰), indicating a very low level of animal protein consumption. This is also suggestive of being raised in a different, more ^{15}N depleted landscape.

The values of $\delta^{13}\text{C}$ (M = -9.0‰ ; SD = 0.48) and $\delta^{15}\text{N}$ (M = 9.6‰ ; SD = 0.04) of the dogs are consistent with their carnivorous diet. One of the individuals, belonging to a dwarf variety, stands out with a $\delta^{13}\text{C}$ value of -18.4‰ , potentially resulting from some consumption of C4 plants (or animal protein from C4 consuming animals).

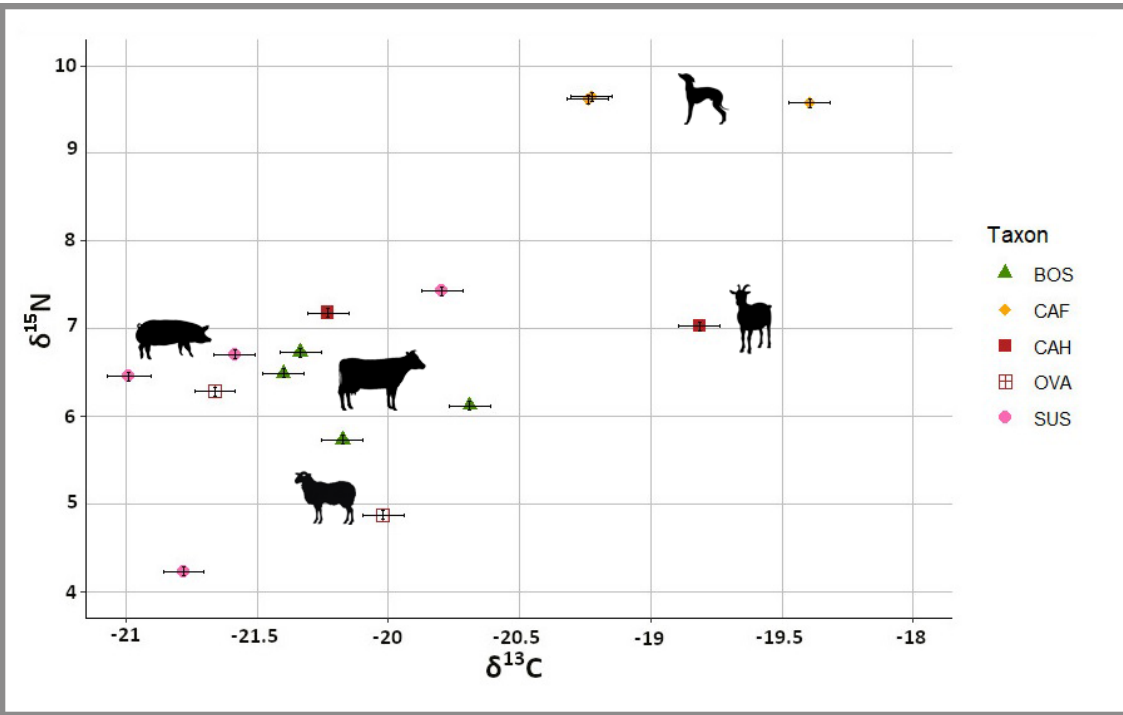


Figure 3. Isotope values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of the fauna recovered from the Easter Baths of the Torreparedones site. Error bars on each sample represent the analytical error for this run.

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

Cattle (TP-1, TP-6 and TP-15) and caprine (TP-2, TP-3 and TP-7) show different patterns and are described and discussed separately.

The results obtained in the sequential stable isotope analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ can be seen in detail in [Table 5](#) and [Figure 4](#).

Identifier 1	Distance from ERJ to sample (mm)	$\delta^{13}\text{C}$ (VPDB)	$\delta^{18}\text{O}$ (VPDB)
TP-1.1	1.3	-11.8	-3.4
TP-1.2	5.8	-11.5	-3.5
TP-1.3	7.9	-12.5	-3.0
TP-1.4	10.5	-12.1	-3.5
TP-1.5	13.0	-11.9	-3.2
TP-1.6	15.2	-12.1	-3.7
TP-1.7	17.5	-12.2	-4.1
TP-1.8	19.8	-12.4	-4.3
TP-2.1	7.2	-11.2	-0.7
TP-2.2	10.7	-11.9	-1.3
TP-2.3	14.1	-12.6	-4.2
TP-2.4	17.8	-12.0	-5.2
TP-2.5	22.6	-11.2	-4.4
TP-2.6	25.3	-10.9	-4.0
TP-2.7	27.7	-11.0	-3.5
TP-2.8	30.1	-10.4	-2.5
TP-3.1	4.0	-11.6	-1.2
TP-3.2	8.7	-12.3	-1.9
TP-3.3	13.3	-10.6	-4.5
TP-3.4	15.9	-10.0	-4.8
TP-3.5	18.7	-9.8	-4.3
TP-3.6	22.1	-9.6	-3.9
TP-3.7	25.6	-10.1	-2.6
TP-3.8	28.5	-10.5	-1.3
TP-6.1	3.8	-9.4	2.1
TP-6.2	9.3	-9.9	-0.8
TP-6.3	15.2	-10.7	-2.1
TP-6.4	20.3	-11.2	-3.1
TP-6.5	27.2	-10.9	-4.0
TP-6.6	32.0	-10.4	-2.2
TP-6.7	37.8	-10.6	-3.2
TP-6.8	43.5	-9.8	-0.5
TP-7.1	5.0	-11.2	-3.7
TP-7.2	7.5	-10.7	-1.5
TP-7.3	10.4	-11.2	-3.1
TP-7.4	13.6	-11.4	-1.6
TP-7.5	16.1	-11.8	-2.2

TP-7.6	20.4	-11.8	-3.6
TP-7.7	20.2	-12.1	-3.3
TP-7.8	26.8	-11.7	-4.0
TP-15.1	5.9	-11.3	-4.1
TP-15.2	9.0	-11.8	-2.6
TP-15.3	12.7	-11.3	-4.6
TP-15.4	16.1	-12.1	-4.4
TP-15.5	16.6	-12.2	-4.3
TP-15.6	18.1	-12.4	-4.6
TP-15.7	21.8	-11.9	-5.3
TP-15.8	24.0	-12.2	-5.3

Table 5. Results of serial analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. All samples have been taken from the lower M3.

Cattle results on the analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ presented mixed results in all their individuals. Cattle TP-1 ($\delta^{13}\text{C} = -11.6\text{‰} - -12.5\text{‰}$; $\delta^{18}\text{O} = -3.0\text{‰} - -4.3\text{‰}$) and TP-15 ($\delta^{13}\text{C} = -11.3\text{‰} - -12.4\text{‰}$; $\delta^{18}\text{O} = -2.6\text{‰} - -5.3\text{‰}$) reflects marked stability in both proxies across the period of their crown's development. The cattle individual TP-6 1 ($\delta^{13}\text{C} = -9.2\text{‰} - -11.2\text{‰}$; $\delta^{18}\text{O} = -0.5\text{‰} - -4.0\text{‰}$) shows a different pattern, with a more stable tendency of $\delta^{13}\text{C}$, with a small increase at the end of the crown's development, but fluctuation in $\delta^{18}\text{O}$ values. Caprines also show a variety of results, with no two individuals showing the same pattern. TP-2 ($\delta^{13}\text{C} = -10.4\text{‰} - -12.6\text{‰}$; $\delta^{18}\text{O} = -0.7\text{‰} - -4.3\text{‰}$) shows a positive correlation in the two proxies which contrasts with TP-3 ($\delta^{13}\text{C} = -9.6\text{‰} - -12.4\text{‰}$; $\delta^{18}\text{O} = -1.2\text{‰} - -4.8\text{‰}$) which shows a strong inverse correlation in their $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values. TP-7 ($\delta^{13}\text{C} = -10.7\text{‰} - -11.8\text{‰}$; $\delta^{18}\text{O} = -1.4\text{‰} - -4.0\text{‰}$) has a similar pattern than the cattle TP-6, with a more stable tendency of $\delta^{13}\text{C}$ but a fluctuation on it $\delta^{18}\text{O}$ values.

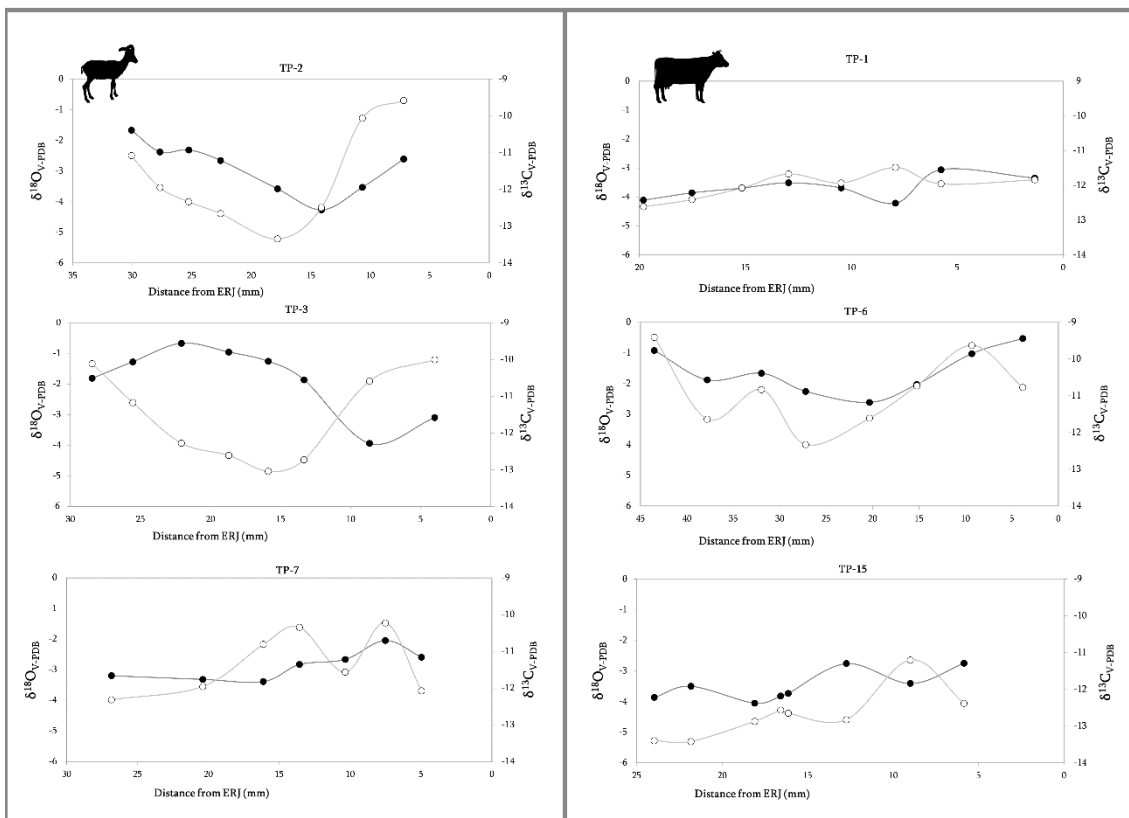


Figure 4. $\delta^{18}\text{O}$ (white dots) and $\delta^{13}\text{C}$ (black dots) sequences for caprine (left) and cattle (right) M3s.

3.3. $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios

The results of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio analysis of the Torreparedones fauna can be seen in Table 6 and Figure 5. The results show a wide degree of variability in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, with values ranging from 0.7083 to 0.7160. Cattle show a bimodal distribution, with individuals TP-6 and TP-14 having a mean value of 0.7087 and individuals TP-1 and TP-15 having a mean value of 0.7160. Caprines had different results between the two species. Sheep values have a mean of 0.7086 while goat values have a mean of 0.7097. Pigs had a mean value of 0.7086, with one outlier, TP-11, which has a value of 0.7134. Dogs had a mean value of 0.7087, with little variation between the three individuals. The results of the analysis of the plant samples gave a range of values of 0.7081 – 0.7089. This has been used in Figure 5 to establish the local range.

Sample	Taxon	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\text{se}$
TP-1	BOS	0.7160	8.26E-06
TP-2	CAH	0.7104	6.70E-06
TP-3	OVA	0.7085	8.58E-06
TP-4	CAF	0.7087	6.94E-06
TP-5	CAH	0.7091	8.02E-06
TP-6	BOS	0.7089	6.96E-06
TP-7	OVA	0.7088	7.58E-06
TP-8	SUS	0.7087	8.22E-06
TP-9	CAF	0.7087	7.98E-06
TP-10	CAF	0.7086	6.92E-06
TP-11	SUS	0.7134	1.03E-05
TP-12	SUS	0.7090	7.76E-06
TP-13	SUS	0.7083	8.16E-06
TP-14	BOS	0.7086	9.52E-06
TP-15	BOS	0.7161	6.28E-06

Table 6. Results of the analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

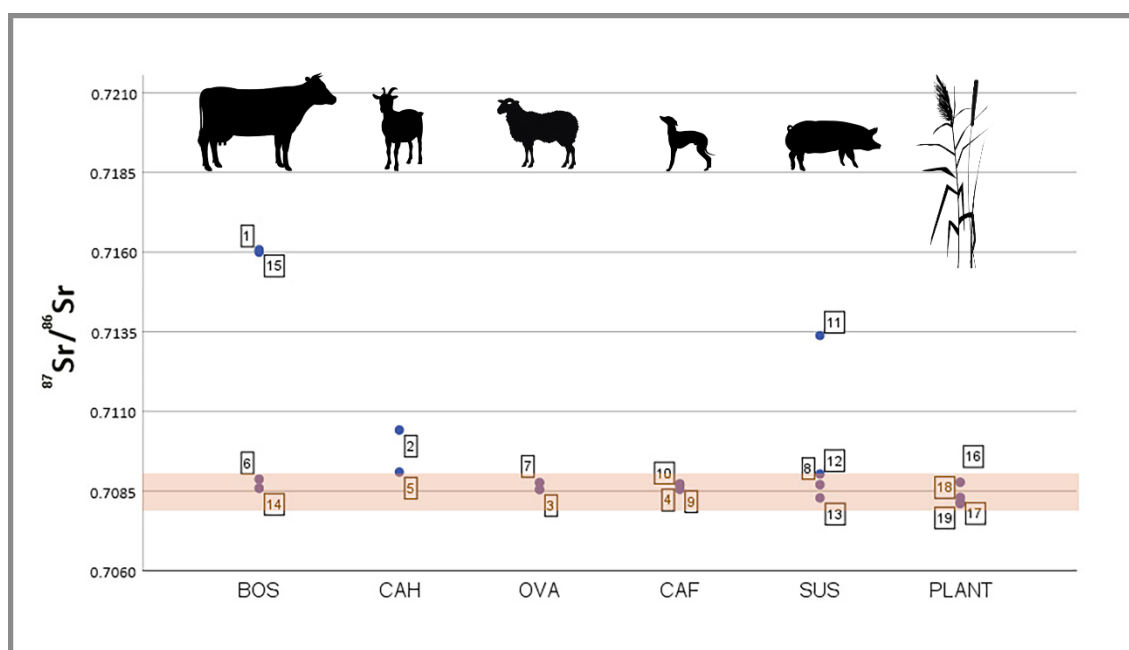


Figure 5. $^{87}\text{Sr}/^{86}\text{Sr}$ values per taxon. The local bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ range based on plant samples marked in orange.

4. Discussion

4.1. Diet

The analysis of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ provides useful data for exploring the diet of the animals at the site. The isotope values of the cattle and goats, with no $\delta^{13}\text{C}$ values higher than -20.5‰, are consistent with a diet based on C3 plants belonging to open ecosystems, such as those found in the Middle Guadalquivir Basin. Pigs show a broadly similar range of values, despite their omnivorous character. Excepting the outliers below, most individuals of all taxa show limited variation, with the four cattle being particularly homogenous, suggestive of the same management regime and a similar range of pasturage. These results are consistent with previous studies carried out on livestock of the Iberian Peninsula from the Roman period, where pigs and other livestock did not show major differences in terms of the isotope footprint on their diet and the contribution of C4 plants was generally limited (García-Moreno et al., 2022; Salazar-García et al., 2023).

One of the goats (TP-5) has higher $\delta^{13}\text{C}$ values than the rest of the herbivore samples. These values are consistent with the effect that grazing in a saline environment has on $\delta^{13}\text{C}$ values (Prummel et al., 2024). Considering the large amount of Triassic salt deposits present in the region (López Ontiveros, 1973), these data could indicate that this goat grazed predominantly in this type of environment.

Another outlying individual is one of the pigs (TP-11) which has the lowest $\delta^{15}\text{N}$ value in the entire dataset, indicating very little consumption of animal protein. This is interesting for an animal with an omnivorous diet; however, pigs with similar isotopic traces have already been observed in Roman times in the Iberian Peninsula (Salazar-García et al., 2023). This low intake of animal protein may indicate different management similar to that of modern-day free-range pigs, though equifinality remains a hurdle to confident interpretation. The outlying value hints at non-local origins, an interpretation supported by the strontium isotope ratio. Origins are likely in a ^{15}N depleted landscape. It is also important to note the advanced age of this individual, with almost total loss of enamel on the upper molars. An interesting question is whether this high plant feeding is the cause of this abnormal wear of the molars due to the consumption of abrasive elements. Plant-heavy diets in pigs tend to relate to forest management, but, although forest ecosystems are isotopically diverse, this typically results in elevated $\delta^{13}\text{C}$ values (see Madgwick et al., 2012, 2019), and TP-11 has the second lowest in the entire dataset. Therefore, it is plausible that fibrous plant material was an important dietary constituent, though pigs do not generally favour this source. This pattern is unusual and a comparative analysis of similar individuals would provide a fruitful future research direction.

The site's dogs have a typical carnivorous diet, being at a trophic level above that of livestock. Individual TP-10 stands out with the highest $\delta^{13}\text{C}$ value in the dataset, thus potentially deriving from a different region. The presence of healed pathologies in the distal region of the tibia and the outlying dietary signal could be indicative of a pet, feeding on waste from human foods.

It should be noted that the number of human remains found at Torreparedones dating to the late Roman period is relatively low. In the future, dating and sampling of available human elements would provide useful information on the management and feeding of livestock and animals on the site and the relationship between human and faunal diets.

4.2. Seasonal mobility

The sequential analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ reveals a series of different management strategies in both caprines and cattle. This could indicate wide-ranging management at the site suggestive of household, rather than standardised husbandry. Alternatively, it could relate to some non-local animals (discussed further below) being subject to different regimes.

Focussing on each taxon, the cattle show two different patterns. First, individuals TP-1 and TP-15 show a stable pattern with low differences between winter and summer peaks. In the Iberian Peninsula (and also Italy) this pattern has been correlated with sedentary husbandry practices with no changes in the graze areas during the year (Tejedor-Rodriguez et al., 2021; Tornero et al., 2018; Trentacoste et al., 2023). The other cattle individual, TP-6, shows relatively stable $\delta^{13}\text{C}$ values, while $\delta^{18}\text{O}$ tends to indicate variation in water sources. This could point to water as the limiting factor in the management of these animals. Considering the low precipitation and the high summer temperatures in this region of Andalusia, this could be indicative of seasonal altitudinal mobility (though not necessarily over a great distance), to find water sources that remained available even in summer. Nevertheless, the possibility of bringing water from distant sources by lead piping or an aqueduct could be the origin of this fluctuation. Unfortunately, no evidence of those infrastructures has been found on the site, but its size and urbanism suggest the existence of such elements (Beltran Fortes, 2010).

Caprines show similarly variable patterns in the sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis. TP-7 shows a similar pattern to TP-6 (cattle), which could again point towards the mobility of the animal based on the availability of water throughout the year. TP-2 shows a positive correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ which could be indicative of a sedentary management strategy, with both diet and water sources varying seasonally in the same location. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is more radiogenic than would be expected for a locally raised animal and therefore this individual could have grazed on an area with different seasonal variation. TP-3 is the only individual that shows a pattern indicative of mobility. The two isotope proxies inversely correlate, which could indicate a change in the grazing location throughout the year. This mobility may not have been over great distances but may rather have been altitudinal, taking into account that Sierra Morena and Subbaetic Mountains are 50 km and 27 km away respectively.

4.3. Assessing bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

The analysis of modern plant samples produced a limited range of low isotope ratios (0.7080-0.7087). These four mixed plant samples provide only limited local characterisation of bioavailability and are not sufficient to represent the totality of geological units present in the Cordovan landscape. However, these samples represent a high percentage of the territory surrounding the site, mostly occupied by an olitostromic unit of clays, marls and clasts of various components, belonging to the Upper Langhian (TP-17) and a unit of turbidites belonging to the Lower Serravalian (TP-16). It is also important to bear in mind that the study area is located in one of the zones of Andalusia with the greatest extension of cultivated fields, so the sampling of natural vegetation not affected by anthropogenic action is an added difficulty to this type of study.

4.4. Mobility

The results obtained through the analysis of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios present one of the first isotope studies of animal mobility in the Roman period in this region. The plant samples demonstrate limited $^{87}\text{Sr}/^{86}\text{Sr}$ variability in the geological formations near the site. The geology is characterised by the marl packages generated by the Miocene marine sedimentation located in

the northwestern part of the area, as opposed to the Tertiary calcareous complexes that dominate the southeastern part at its junction with the foothill of the Subbaetic Mountains, which are combined with the Quaternary fluvial contribution and the extreme anthropization caused by modern farming. All this generates a relatively mixed landscape and very little biosphere mapping has been undertaken in the area (Frank et al., 2022). However, the plant data, whilst not providing comprehensive coverage, provide an indication of the biosphere of the local geological environment of the site, which covers more than 15 km (Figure 2). Consequently, animals with values that fall within the range of the plant samples can be considered consistent with being locally raised, but this is not to say that they could not have derived from elsewhere. Similarly, animals with different values could also be from the surrounding region, given the limited plant sampling.

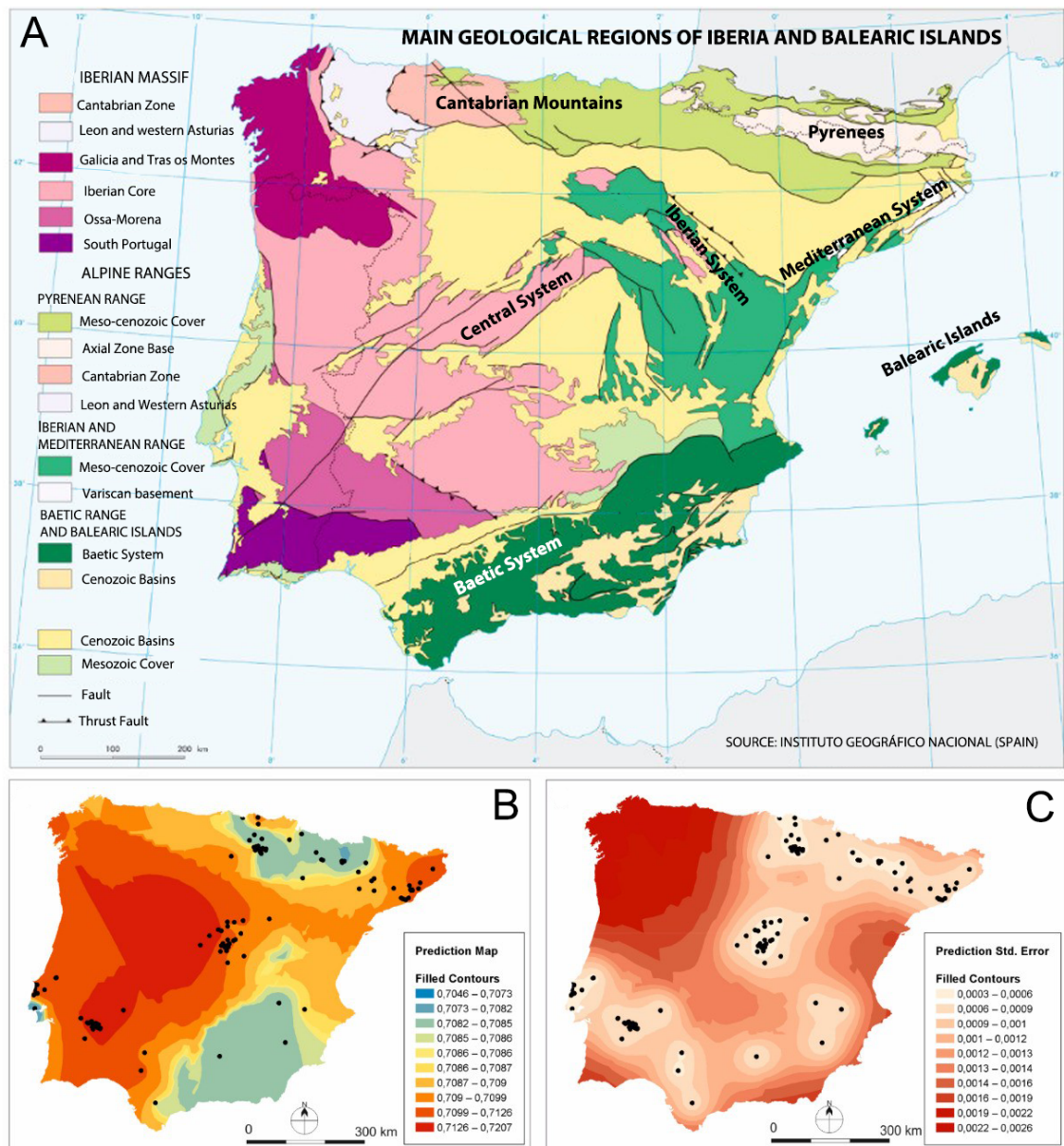


Figure 6. Predictive model from Diaz-del-Río et al., (2022). A: Simplified geological map of the Iberian Peninsula. Source: Mapa de grandes regiones geológicas de la Península Ibérica y Baleares. Spanish Government, Public Domain. Below: Predictive $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape models for the Iberian Peninsula. B. all samples, C. Prediction standard error map for all samples.

Based on the analysis of bioavailability, 9 of the 15 individuals are consistent with being locally raised (Figure 5). Three of the four taxa comprise both local and non-local individuals. Only the goat dataset differs in having only individuals with radiogenic Sr isotope ratios that are inconsistent with the immediate vicinity of the site. However, neither radically outlie and one (TP-2) is very close to the local range and could be locally raised given the limited plant sampling programme. Relating these results with the prediction maps created by Díaz-del-Río et al. (2022) provides some indication of the likely origins of the livestock (Figure 6). First, the individuals marked as local, as well as the plant samples, could be correlated with the estimated values for Guadalquivir Basin and Subbaetic Mountains. The values observed in the goat TP-5 and the pig TP-12, even being outside of the local range, could be related to the Guadalquivir Basin, but also to the eastern limit of Sierra Morena and the Central Subsystem. Finally, the last two cattle TP-1 and TP-15 and one of the pigs, TP-11 have values consistent with the western zones of the central subsystem. This could place the origin of these individuals hundreds of kilometres away. However, it is important to note that this interpretation is based on a predictive map and more extensive primary plant sampling would certainly necessitate revisions in this characterisation (Holt et al., 2021). This is especially relevant considering that only five samples have been taken from Andalusia, being the closest to Torreparedones more than 50 km away (Díaz-del-Río et al., 2022).

There is also the possibility that some of these animals came to the site in the form of meat portions already butchered. Considering all the anatomical parts analysed in this work are mandibles and maxillae, which would rarely be traded or transported with the rest of the animal's carcass. Their age of slaughter and the particularly old individuals also support the hypothesis that the animals were moved when alive. Other factors that support this hypothesis are the extensive butcher activity described in the study of the Macellum of the site (Morena López et al., 2012) and the relevance of the bone craftsmen as the end of a complex production change (Guillamón Dávila & Martínez Sánchez, 2023).

Other isotope proxies can aid in the exploration of non-local individuals and their potential origins. The $\delta^{13}\text{C}$ isotope value of goat TP-5 suggested the consumption of plants from saline soils. Considering this kind of soil is present in the Cordoba countryside, especially in the Guadajoz basin (López Ontiveros, 1973), the slightly higher ratios in the $^{87}\text{Sr}/^{86}\text{Sr}$ analysis could reflect the mobility of this goat in a 30 km area, possibly marking the catchment where these animals could have moved as part of their grazing activity.

Pig TP-11 has an outlying $\delta^{13}\text{C}$ value, demonstrating very limited animal protein consumption. This could again, be indicative of different management from other individuals from the site, not because of some special status, but because of different origins and therefore varied practices carried out elsewhere.

Regarding cattle, two of the four individuals have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios consistent with local origins. As with all taxa in the dataset, this should not be considered representative. The studies carried out to date highlight the importance of cattle both in terms of importance and number at Torreparedones (Martínez Sánchez and Moreno Rosa, 2017; Morena López et al., 2012). Extending the cattle sample is necessary to clarify the dynamics of management of this key domesticated in the faunal economy.

The two sampled sheep are consistent with local origins. This is surprising for individual TP-3, which shows clear evidence of a change in grazing altitude. The low altitude of the Guadalquivir Valley makes it unlikely this management strategy could be carried out in the city, considering

the site is one of the highest points in the area, standing at an elevation of 552 m above sea level. However, it is quite plausible that these transhumant management practices were carried out in a different area, but with similar geology. If this is indicative of a transhumance route that passes through the site is difficult to say with only one individual showing these characteristics. The analysis of multiple $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in samples through the axis of the tooth, combined with the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ enamel sequence would help to clarify this issue, as demonstrated in a broadly contemporaneous study in Iberia by Messana et al. (2023).

The three dogs all have values consistent with local origin. This is particularly interesting in individual TP-10, which, based on zooarchaeological analysis, belongs to a breed related to badger hounds and whose $\delta^{13}\text{C}$ analysis indicates a greater consumption of plant foods. If this animal was a pet or a specialised hound, its local origin suggests the breed was at least somewhat established (i.e. at least second generation) in the city, rather than being a recently imported acquisition.

5. Conclusions

The multi-isotope analysis at Torreparedones provides a new perspective on human-faunal relations and livestock management as an economic practice in the south of the Iberian Peninsula during the Roman period. It is particularly interesting to explore practices in a period marked by the abandonment of public infrastructures due to a socio-economic crisis. The husbandry practices in evidence are consistent with traditional extensive livestock management and apply to cattle, caprines and pigs and appear quite diverse in this limited dataset. In some instances, differences in faunal diet and management can be related to a different origin of the individuals, demonstrating variable management carried out by different populations in the area. Isotope data for dogs, combined with zooarchaeological evidence, suggest that some may have been pets, fed a particular diet and deposited in a specific manner. The addition of different breeds of domestic dogs to this type of analysis would markedly enhance our understanding of the dynamics of management and supply in Roman Iberia.

This study is one of the first to explore faunal mobility using multiple isotope proxies on the Roman period in the south of the Iberian Peninsula. Even though the majority of the individuals are consistent with local provenance, all taxa except dogs have evidence for non-local individuals. However, the limited number of samples cannot provide a comprehensive picture of husbandry regimes and the dynamics of the faunal economy at the site. Based on the prediction models made by Diaz del Rio et al. (2021), the commercial routes that bring livestock to the city could extend hundreds of kilometres to the north, maybe following ancient routes used for centuries. In any case, biosphere mapping remains in its infancy in Iberia therefore identifying precise origins is not currently possible. The site's dogs have a markedly local character, which is especially relevant for one of the individuals belonging to a dwarf breed, whose foreign origin is ruled out through the acquisition of exotic varieties. In the future, increasing the sample size and sampling per individual will not only allow the observation of patterns in different taxa, but also facilitate tracing diachronic changes in the mobility of individuals.

The application of seasonal mobility of the cattle and caprine livestock provides a diverse pattern of management in the context of the specific landscape characteristics of the region. A great variety of seasonal management strategies are evidenced that could also be related to the foraging origin of the animals. Whilst more research on local fauna is required, it is plausible that

local livestock needed to be moved to find water sources in the summer season and this movement may have principally been altitudinal.

The research adds important data to a limited corpus of isotope results for domestic animals in Roman Hispania, providing new insights into the production, supply, and consumption of cattle, sheep/goats, and pigs in a city immersed in a rural landscape. Even with the small sample size of this work, the study has attempted to present the strongest hypotheses based on the information known about the site and the territory. This study aims to provide a baseline or a starting point for further studies on livestock practices and animal mobility in Roman Hispania.

6. Acknowledgements

Special thanks go to the Baena Town Council for funding this project, to Jose Antonio Morena López for his help and advice on the project, to Roger Alcàntara Fors, Leïa Mion, Hongjiao Ma and Katherine French for their training and assistance in the laboratory work, to Marc-Alban Millet and Edward Inglis for their assistance in the CELTIC facilities and to the anonymous reviewers and the co-editor Ellery Frahm for improving this article through their review.

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