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Intensive resource exploitation in Late Neolithic Iberia: Bone marrow and subsistence changes at Branqueiras, central-coastal Portugal

Cláudia Costa [a,*], Maria João Fernandes Martins [a], Vera Cardoso [b], Guilherme Cardoso [c], António Faustino Carvalho [d]

[a] ICArEHB – Interdisciplinary Center for Archaeology and Evolution of Human Behaviour, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[b] Sabugueiro – Associação de Proteção Ambiental, Cultural e Arqueológica do Alto Côa, Largo da Praça 8, 6320 Sabugal, Portugal
[c] Associação Cultural de Cascais, Av. Infante D. Henrique, 106, 11.°, 2750-167 Cascais, Portugal
[d] CEAACP – Centro de Estudos de Arqueologia, Artes e Ciências do Património/polo UAlg , Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

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ABSTRACT

The exploitation of bone marrow has long been recognised as a vital component of past human subsistence strategies, particularly for its nutritional value. While this practice is well studied in hunter-gatherer societies and in communities facing harsh environmental conditions, it is less understood in prehistoric farming societies and temperate environments. This paper presents the results of bone marrow exploitation at the Late Neolithic short-term site of Branqueiras, located in the temperate central-coastal region of Portugal. The faunal assemblage reveals a significant percentage of intentional long bone breakage for marrow extraction, a practice that appears to have been overlooked in earlier and later periods. The site's short-term occupation, radiocarbon-dated to 2900–2700 cal BC, coincides with a hiatus at the nearby long-term settlement of Leceia and occurred during a period of climate change characterised by reduced rainfall, hot summers, and cold winters. This study provides key insights into human adaptation to climate stress within established farming communities, a topic often underexplored in Neolithic–Chalcolithic contexts. The authors propose that the Branqueiras community represents a shift in human behaviour, as itinerant groups adapted to arid conditions by intensively exploiting animal resources, including domestic caprines, swine, wild game, and molluscs, while agricultural practices and cattle herding declined. In this context, bone marrow became a crucial source of nutrients, playing a significant role in subsistence strategies during this challenging period.

1. Introduction

Fat is essential for human body function, contributing to both physiological and psychological processes. It provides more calories than carbohydrates or protein, regulates hormone activity, and acts as a vehicle for the transport of vitamins A, D, E, and K. Fat also enhances the palatability and the flavour of food (Kritchevsky, 2002). Therefore, the procurement of fat in past societies was one of the most important activities and played a key role in human evolution (e.g., Leonard et al., 2010). Animal fat is a readily available and efficient source of this nutritional input. Animal meat provides adipose, muscular, and connective tissues, and it is well known that bone fat—both bone marrow and bone grease—is an important source of fat. The consumption of bone fat has been widely studied among hunter-gatherers, particularly in harsh environments or when mammals are lean (e.g., Breslawski et al., 2015; Blasco et al., 2019; Christensen et al. 2018; Munro and Bar-Oz, 2005; Lupo, 1998; Outram, 2001, 2003, 2005) and in ethnoarchaeological studies (e.g., Binford, 1978; Oliver, 1993). It must be acknowledged that the exploitation of bone marrow is not always associated with extreme need; indeed, consumption of bone fat is currently appreciated in various cuisines globally, being for example especially esteemed in the traditional Portuguese dish *cozido*. In addition to food consumption, bone fat can be used in craft industries, particularly in the treatment of animal skins and tanning (Outram, 2001: 401).

However, research on bone fat exploitation in post-Pleistocene temperate environments is underdeveloped, particularly among prehistoric farming communities. Recent research has identified bone marrow extraction at LBK sites from Central Europe (Johnson et al., 2018; Smyth et al., 2023), as well as in some Early and Late Neolithic Greek sites (Halstead, 2020; Samartzidou and Hourmouziadis, 2024).

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* Corresponding author.
E-mail addresses: cmcosta@ualg.pt (C. Costa), mjfmartins@ualg.pt (M.J. Fernandes Martins), afcarva@ualg.pt (A.F. Carvalho).

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Reviews of faunal assemblages in British causewayed enclosures have also demonstrated that this practice was part of the rituals of feasting in monumental Neolithic and Bronze Age enclosures (Parmenter et al., 2015).

Evidence for marrow extraction at sites in Portugal dating from the fourth to the second millennia BC is extremely rare. The vertebrate faunal assemblage from Branqueiras, which dates to the Late Neolithic (end of fourth millennium BC), comprises a small collection from a short-term occupation site found in the highly urbanised area of Cascais (Lisbon), containing only a few identifiable elements. However, the taphonomic analysis of the principal feature reveals a notable particularity: the presence of long bone shafts exhibiting clear evidence of systematic bone marrow exploitation. This finding contributes to the ongoing debate concerning the exploitation of bone fat during the Neolithic. Given the scarcity of data from earlier and contemporaneous contexts, we argue that investigating the behaviour of the community that occupied this central-coastal Portuguese site provides valuable insights into the practice of bone marrow extraction in Iberian Late Prehistory and the probable intensification of resource exploitation, particularly during periods of environmental stress.

2. Branqueiras

2.1. *The site*

Branqueiras is an open-air archaeological site located in the municipality of Cascais, near Lisbon, on the westernmost tip of continental Europe. The site is situated on a mid-slope promontory at approximately 50 m a.s.l. This topography is further emphasised by the meandering Vinhas stream, which cuts through the local Cretaceous limestone and meets the Atlantic ca. 2 km downstream (Fig. 1, A and B). Due to human activities such as ploughing, limestone quarrying, and more recently, urbanisation, it has not been possible to estimate the site’s original total area.

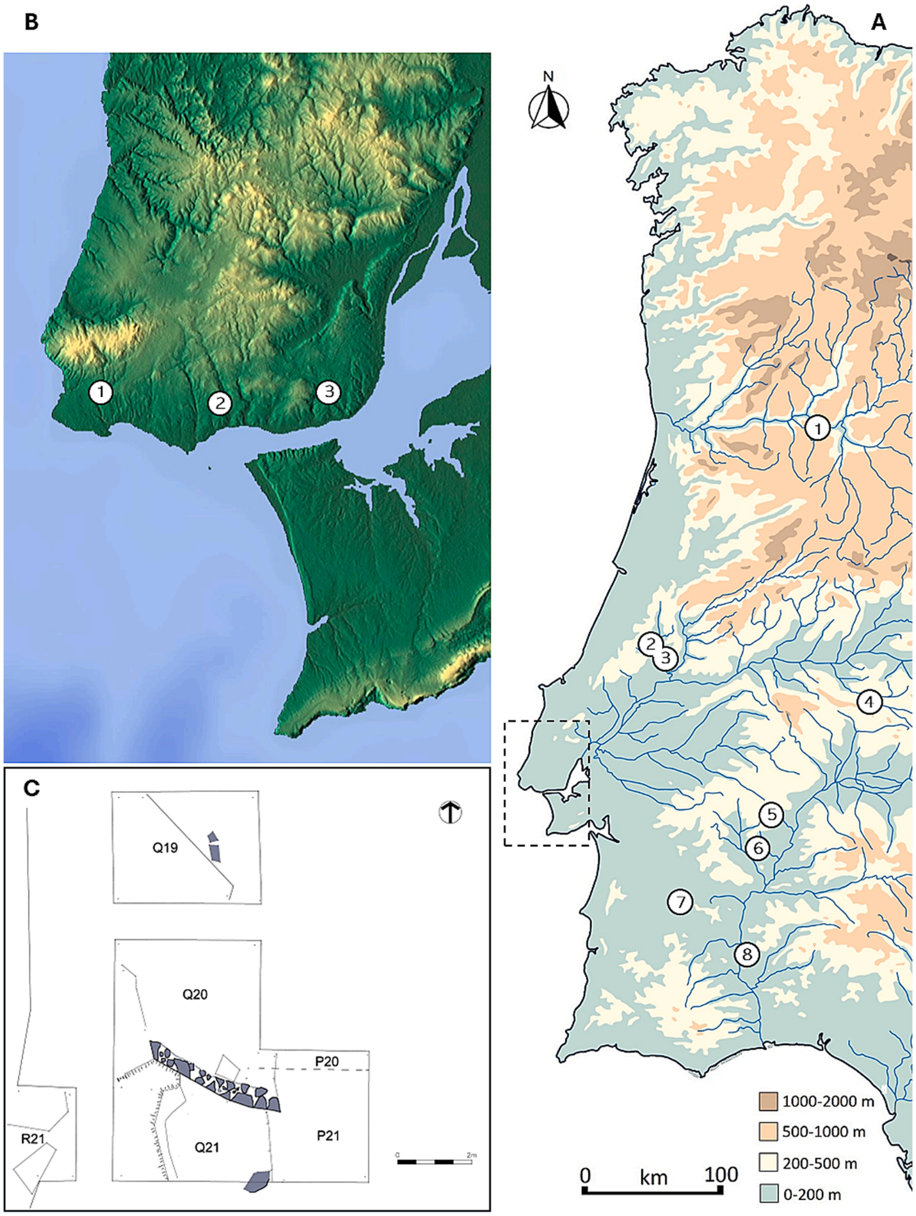

Fig. 1. Location of sites mentioned in text. A) Western Iberian comparison sites – 1. Castanheiro do Vento; 2. Nossa Senhora das Lapas Cave; 3. Cadaval Cave; 4. Los Barruecos; 5. Montoito 2; 6. Perdigões; 7. Barranco do Xacafre; 8. Montinhos 6. B) Sites of the Lisbon Peninsula – 1. Branqueiras; 2. Leceia; 3. Encosta de Sant’Ana. C) Excavation plan of Branqueiras (with indication of excavated square units).

Discovered in the early 1970 s, Branqueiras was already included in the municipality's archaeological map (Cardoso, 1991) when a rescue excavation was conducted in 1998, prior to the construction of a housing development. To date, only a brief preliminary report on the site has been published (Cardoso, 1998), and it is currently under further study.

The excavation strategy involved the successive opening of five areas where the concentration of archaeological materials-particularly in the interstices caused by the dissolution of limestone surfaces (*lapiaz*) was most significant. Total excavation covered an area of 55.5 m^2 (Fig. 1, C).

The stratigraphy, which varied between excavation areas, comprises several units of clayish sediments differing in compaction and colour (reddish or brownish). The uppermost units (layer 1), corresponding to the ploughed horizon, contained coarse pottery from the eighteenth and nineteenth centuries. In another area, collapsed stones from a traditional wall (layer 2) overlay the prehistoric occupation layer (layer 3), which lies directly on the limestone bedrock. Although the prehistoric material was here less abundant than in the upper layers, it was still *in situ*, allowing for the identification of Late Neolithic artefacts associated with faunal remains (Table1).

An east–west masonry wall, measuring 0.8 m in width and 3 m long, was also uncovered. This wall likely formed part of a larger structure that could not be fully identified due to the extensive ploughing, quarrying, and subsequent road construction at the site. Small rubbish dumps containing faunal remains were found on both sides of the wall base.

Branqueiras has yielded material culture typical of the Late Neolithic period, with parallels in other sites within the Lisbon region, most notably in layer 4 of Leceia (for an overview, see Cardoso, 2004). The assemblage consists predominantly of undecorated pottery, including carinated bowls and jagged-rim vessels (respectively, "*taças carenadas*" and "*vasos de bordo denteado*" in the commonly used Portuguese terminology). Additionally, polished stone tools (axes) and a significant quantity of flint artefacts, including debitage, indicate knapping activities at the site. Among the flint artefacts, bifacially retouched arrowheads and possible sickle implements are particularly noteworthy, the former being commonly present in contexts from the Late Neolithic onwards.

2.2. *Radiocarbon dating*

Conventional radiocarbon dating of four samples was performed at the former *Instituto de Tecnologia Nuclear* (ITN) laboratory in Portugal using unidentified animal mammal bones and shells of Common cockle (*Cerastoderma edule*). Calibration was estimated using the online software OxCal v. 4.4.4 (Bronk Ramsey, 2021) making use of calibration curve IntCal20 (Reimer et al., 2020) for terrestrial samples, and Marine20 (Heaton et al., 2020) to marine samples. Western Atlantic cost value used was 95 ± 15 years ^{14}C for the correction of the marine reservoir (ΔR), as determined by Soares and Dias (2006). Results are presented in Table 1 and Fig. 2.

The occupation of Branqueiras occurred between approximately 2900 and 2700 cal BC (Fig. 2), consistent with the site's material culture (as described above), which is characteristic of the Late Neolithic in the region.

Notably, the aforementioned time period aligns with the hiatus identified at Leceia—the primary comparison site for Branqueiras in the area (see below)—between its Late Neolithic and Initial Chalcolithic occupation phases. According to Soares and Cardoso (1995: Table 2), the former occupation phase at Leceia is dated to 3500–2900 cal BC, while the latter is dated to 2870–2400 cal BC, at a 90 % probability. The implications of this fact for the Neolithic-Chalcolithic transition in the area will be addressed in the discussion section.

3. Material and methods

A total of 549 specimens were examined, of which 109 are loose teeth, most of them fragments. These were manually collected during the excavation of various archaeological contexts. The clayey nature of the soils, which were sometimes very hard, did not favour the sieving of sediments. Thus, excavation was carefully undertaken by artificial levels of 5 cm monitoring the natural layers and all archaeological material was manually collected. Using this approach, material containing small osteological remains of leporids and birds along with fish vertebrae were exhumed (see below). Therefore, the present assemblage can be considered as representative of the original record.

3.1. *Taxonomic and anatomic identification*

All remains comprising the faunal assemblage were individually examined and identified both anatomically and taxonomically, following modern zooarchaeological procedures as outlined by Binford (1981), Lyman (1994), and Reitz and Wing (2008). Taxonomic identification was conducted using the reference collection of the Osteo-Archaeology Lab at ICArEHB and reference collection from Archaeosciences Lab from the Portuguese heritage institute (Património Cultural, I.P.).

Certain *taxa* were difficult to distinguish at the species level. Iberian wild boars, for instance, have dimensions very similar to those of their domestic counterparts, necessitating the use of osteometric analysis of specific skeletal elements to differentiate them from domestic pigs (Albarella et al., 2005). Given the poor preservation conditions of the present collection, which is highly fragmented, it was not possible to apply this methodology. Therefore, all suid remains were classified only at the genus level, *Sus* sp.

Sheep (*Ovis aries*) and domestic goats (*Capra hircus*) have very similar skeletal morphologies, making their distinction possible only when diagnostic elements are preserved. In the present assemblage, only one

Table 1
Radiocarbon dating results.

Ref. Lab.	Sample	Archaeological context (excavation area and layer)	$\delta^{13}C$ (‰)	Date ^{14}C (BP)	Calibration (cal BC; % prob.)	
					1σ	2σ
Sac-2131	Unidentified mammal bones (colagen)	Q21 (3)	−20.11	4240 ± 50	2911–2861 (35.2); 2805–2755 (26.1), 2720–2703 (7.0)	3005–2992 (0.8); 2928–2831 (43.7); 2823–2663 (49.6); 2652–2632 (1.4)
Sac-2127	Shells of *Cerastoderma edule*	Q21 (3)	+0.81	4650 ± 45	2713—2498 (68.3)	2839–2439 (95.4)
Sac-2130	Unidentified mammal bones (colagen)	Q20 (2/3)	−20.99	4210 ± 60	2899–2847 (21.9); 2811–2743 (29.9); 2730–2693 (13.9); 2686–2677 (2.6)	2916–2621 (94.2); 2601–2584 (1.3)
Sac-2129	Shells of *Cerastoderma edule*	Q20 (2/3)	+1.09	4830 ± 40	−2923—2738 (68.3)	3021–2634 (95.4)

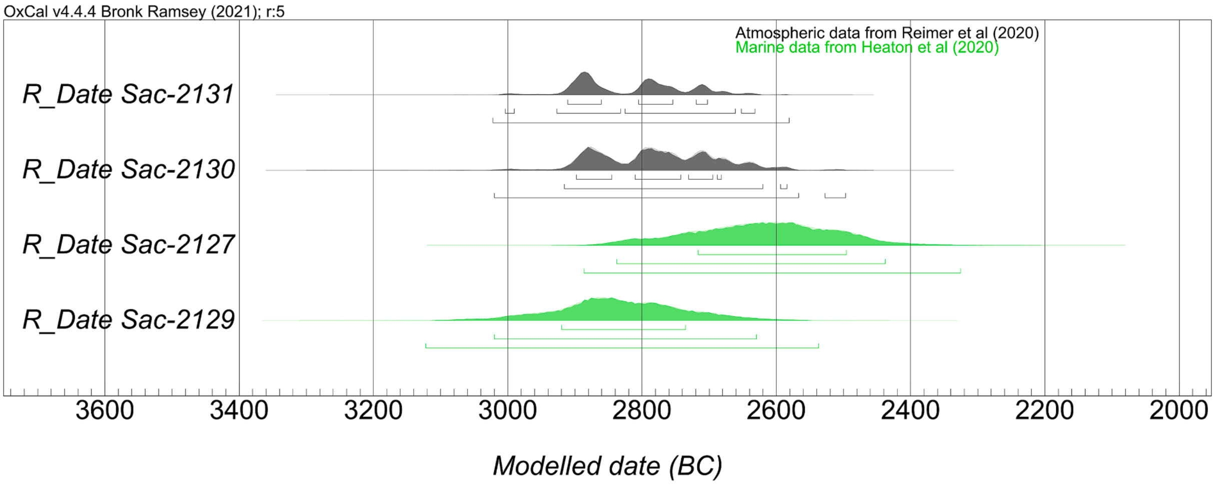

Fig. 2. Modelling of the radiocarbon dates calibration (after Bronk Ramsey 2021).

Table 2
Specific damage patterns from bone grease rendering and bone marrow exploitation on faunal remains.

Characteristics	Bone marrow	Bone grease rendering	References
Fragmentation	High fragmentation of long bones	High Fragmentation of cancellous (spongy) bone ends	e.g. Heinrich (2014), Manne (2014), Morin (2020), Outram (2001), Bemilli (2018)
Percussive impact marks	Presence of percussion marks	Abundant percussive impact marks	
Fractures	Fresh (green) bone fractures, which are characterized by spiral or oblique fracture surfaces.	Breakage of fresh (green) bone, displaying spiral or oblique fractures.	
Frequency of whole bones	High frequency of articular ends that remain mostly intact.	Low percentage of whole bones; highly fragmented bones; very few complete or nearly complete elements.	
Fragment size	Broken into a few large pieces rather than being highly comminute; shaft fragments are commonly large enough to be refitted	Extensive fragmentation; small fragment size; bones are broken into very small pieces, often less than 30 mm	

specimen was confidently assigned to sheep using the methods published by Boessneck (1969) and Zeder and Lapham (2010). All other specimens of this group were classified as belonging to the ovicaprine stock (subfamily Caprinae), which includes both sheep and goats (*Ovis/Capra*).

The remaining bones were grouped as microfauna (e.g., rodents), small-sized mammals (e.g., leporids), medium-sized mammals (e.g., suids, sheep, and goats), and large-sized mammals (e.g., red deer and cattle).

To assess species relative abundance, the Number of Identified Specimens (NISP) was calculated and the estimation of the minimum number of individuals (MNI) was conducted by counting the most represented bone zone (Grayson 1984; Lyman 2008).

The analysis also included the observation of anthropogenic manipulation and other taphonomic signatures on bone surfaces, such as percussion marks, cut marks, burning, animal gnawing, vermiculation from terrestrial gastropods, root etching and oxide precipitation (e.g., Blumenschine, 1995; Fisher, 1995; Costa, 2013).

3.2. Distinguishing bone fractures

The characterisation of faunal remains breakage is a significant issue in zooarchaeological studies and is typically the most representative taphonomic signature in faunal assemblages. It can be attributed to various natural agents (e.g., climatic conditions, carnivore activity) as well as anthropogenic factors. The morphology of different types of breakage enables inferences about the origin of the accumulators (e.g., references listed in Lyman, 1994).

Fractures from the Branqueiras assemblage were recorded for each bone and tooth and classified into three categories: excavation breaks (EB), dry breaks (DB), and green breaks (GB). EB, which occur during excavation or post-excavation handling, typically exhibit a lighter colour than the surrounding bone surface. DB are older fractures, usually sustained when the skeletal element was already dry (i.e., lacking the plasticity characteristic of fresh bone). These are characterised by irregular, asymmetrical fracture surfaces and, when preserved in the transverse plane, right-angled edges. Such features may result from a range of post-depositional processes, including slope dynamics and trampling.

GB were recorded exclusively on bones. This type of breakage occurs when the bone is still fresh-post-butchered but prior to decomposition, drying, or fossilisation-thus retaining some soft tissue. These breaks are typically spiral, curved, or helicoidal in the transverse plane of long bones and are characterised by smooth, convex fracture surfaces with acute or obtuse angles relative to the cortical surface (e.g., Outram, 2001, 2002, 2003; Bemilli, 2018). Breaks of this type were recorded following the methodology outlined by Outram (2001, 2002, 2003).

Green breaks are commonly associated with the deliberate fracturing of long bones to access the marrow cavity. This differs from bone grease rendering, which tends to affect cancellous bones such as epiphyses and vertebrae (Table 2) (e.g., Outram, 2001, Heinrich, 2014, Manne, 2014, Morin, 2020). Green break features are thus distinguishable from those resulting from post-depositional breakage processes (e.g., slope dynamics), which tend to produce different mechanical signatures like the ones described above (e.g., Blumenschine and Selvaggio, 1988).

Percussion leaves characteristic impact marks on the cortical and internal surfaces of the bones, showing internal notches (Morlan, 1984; Johnson, 1985; Outram, 2001, 2002; Blumenschine and Selvaggio, 1988). These marks, both notches in long bones, as percussion bulb and impact points in small splinters, were also recorded and assigned to anatomical and taxonomic classifications.

To analyse fragmentation patterns, every specimen with old breaks-both green and dry-was measured for total length using a digital Mitutoyo calliper. Measurements were recorded in millimetres (mm) and rounded to the nearest decimal place. Graphical outputs were generated using R v. 4.4.1 (R Core Team, 2024).

4. Results of the zooarchaeological analysis

4.1. Taxonomic list

Table 3 present the taxonomic list and the non-identifiable specimens; Table 4 show the anatomical representation of each taxon. Pigs/boars (*Sus* sp.) are the most represented taxon in terms of the number of identified specimens (NISP) (n = 56), heavily influenced by the abundance of loose teeth (n = 33), most of which are fragmented. A minimum number of individuals (MNI) of two was calculated. The assessment of the maturity of the specimens suggests the presence of adult individuals.

Domestic caprines (*Ovis/Capra*) are the second most abundant taxon in NISP (n = 43). Only a complete distal epiphysis of the humerus, with well-preserved diagnostic features, allowed identification as sheep (*Ovis aries*). The remaining specimens were classified as belonging to the *Ovis/Capra* group. As observed in the *Sus* sp. group, the number of domestic caprines is inflated by the presence of loose dental elements (n = 34), many of which are fragmented. The presence of two molar zones from two right mandibles allowed for the calculation of a minimum of two individuals. The general state of maturity of the elements suggests that the individuals were adults at the time of death.

Domestic cattle (*Bos taurus*), like suids and caprines, are over-represented by the presence of loose teeth (n = 3), the majority of which are also fragmented. The size of the elements is consistent with the domesticated species-except for two small teeth fragments, that were classified to genus only (*Bos* sp.)-, which is much smaller than the aurochs. The post-cranial elements suggest the presence of a single mature individual.

Red deer (*Cervus elaphus*) are represented by five elements. However, the presence of a phalanx from an immature individual allowed for the calculation of a minimum number of two individuals in the assemblage. Their anatomical representation (Table 4), with no identified dental elements and the presence of a calcaneus, a metacarpal, and two metatarsal fragments, does not allow for definitive conclusions regarding the effectiveness of human predation.

Rabbits (*Oryctolagus cuniculus*) are present in the assemblage and would certainly have been a resource available in the vicinity of the site, despite their low representation (n = 4). The presence of anatomically significant elements from a meat consumption perspective (i.e., humeri and femura) clearly points to their predation by the human community.

Table 3
Taxonomic data with number of identified specimens (NISP) and minimum number of individuals (MNI).

Taxon	NISP	% NISP	MNI
Ungulate	35	6,6	
Sus sp.	56	10,2	2
Cervus elaphus	5	0,9	2
Bos sp.	2	0,4	1
Bos taurus	11	2,0	1
Ovis/Capra	43	7,8	2
Ovis aries	1	0,2	1
Canis familiaris	2	0,4	1
cf. *Canis familiaris*	1	0,2	1
Oryctolagus cuniculus	4	0,7	1
Micromammal	1	0,2	1
Small size mammal	5	0,9	
Midium size mammal	73	13,3	
Large size mammal	14	2,6	
Unidentified mammal	294	53,6	
Bird	1	0,2	1
Fish	1	0,2	1
Total	549	100	14

The dog (*Canis familiaris*) is represented by only three elements, one of which is a fragmented lower first molar. Due to the fragmentation of the teeth, it was carefully assigned as cf. *Canis familiaris*. Assuming this identification is correct, the MNI is 1.

The presence of a bird's first phalanx was also recognised, as well as an unclassified fish vertebra. Common cockle (*Cerastoderma edule*), limpets (*Patela* sp.), scallop (*Pecten* sp.) and other shellfish such as *Phorcus* sp. and other Trochidae were also recovered. These non-mammal remains are presently under further analysis.

4.2. Taphonomic data

The assemblage exhibits significant fragmentation due to excavation breaks, dry breaks, and green (fresh) breaks (Table 5). Consequently, only 29.5 % (n = 161) of the faunal remains was assigned to a general taxonomic classification, and 22.6 % (n = 125) was classified to the genus and species levels. This is evident in Table 4, which highlights the high percentage of loose teeth (n = 109, approximately 20 % of the total assemblage), most of which are fragmented. Only 31 bones and teeth are complete. However, all anatomical parts of three main *taxa* (*Sus* sp., *Ovis/Capra*, and *Bos taurus*) are present in the assemblage, suggesting butchery of those animals at the site.

Carnivore gnawing was identified on a total of 10 bones, all of which display round pitted marks consistent with carnivore gnawing. Anthropogenic marks, such as spiral and curved fractures (consistent with green breaks), percussion marks, cutmarks and burning, were observed on a total of 147 bones, comprising 26.6 % of the entire assemblage (Table 4), the majority are green breaks (n = 107) (Table 6) including two splinters. Additionally, eighteen burnt bones were collected, along with 13 bones showing percussion marks, five bones with cut marks (Figs. 3 and 4) and four bones exhibiting signs of intentional polishing.

All specimens display varying stages of staining due to manganese and iron oxide precipitation, which is typical in sites with limestone substrates. Root etching was also observed (n = 22). Signs of corrosion were evident on a few bones (n = 5), likely due to the high alkalinity of the soil. Overall, aside from dry bone breakages, the bone surfaces are generally well preserved.

Regarding fragmentation, 25 % (n = 137) of the assemblage was excluded from the analysis due to excavation break. Consequently, 270 dry break specimens, including tooth fragments, were measured. The histogram (Fig. 5) illustrates a right-skewed distribution, with most data present between 10 mm and 30 mm, while measurements greater than 40 mm are relatively infrequent. The skewness suggests that smaller values are more common, while larger values occur less frequently. This is the expected pattern in an archaeological site with the topography of Branqueiras and the natural and anthropogenic post-depositional disturbances. On one hand the archaeological layers were formed in a mid-slope platform and erosion dynamics played a significant role after the abandonment of the site. On the other hand, modern human activities at the site, namely the collapse of an old stone structure and ploughing, further affected the assemblage's physical integrity.

4.3. Bone fat exploitation

As shown in Table 5, a total of 107 bones (24.4 %) exhibited a helicoidal and curved shape on the transverse surface, with smooth fractures and sharp angles (both obtuse and acute) relative to the cortical surface. Combinations of green breakage with other fragmentation types were also recorded: Green break + Dry break (n = 13), and Green break + Excavation break (n = 21) (Table 5 and Fig. 6).

The bones selected for measurement were those that exhibited fresh fractures in their transverse plane allowing measurement along their longitudinal axis. Therefore, to the 73 bones with green breakage, 4 bones with the Gb + Eb combination and 13 with the Gb + Db combination were added to the measurements. In total, 90 bones with green

Table 4
Anatomical representation.

Anatomic elements	Ungulata	*Sus* sp.	*Cervus elaphus*	*Bos* sp.	*Bos taurus*	*Ovis/ Capra*	*Ovis aries*	cf. *Canis familiaris*	*Canis familiaris*	*Oryctolagus cuniculus*	Microfauna	Fish	Bird
Horn						1							
Loose teeth	34	33		2	5	34		1					
Petrous		1											
Mandile						2							
Vertebrae											1	1	
Scapula		4											
Humerus		1				1	1			1			
Radius		2								1			
Ulnae		2											
Metacarpal			2										
3rd Metacarpal		1											
Innominate		1											
Femur										1			
Tíbia										1			
Astragalus		1	1			1							
Calcaneus		1							1				
Metatarsal			1		2	1							
2nd Metatarsal													
Metapodium	1	2			2				1				
1st Phalange		3	1			2							1
2nd Phalange		2			2								
3rd Phalange		1											
Total	35	52	5	2	11	43	1	1	2	4	1	1	

Table 5
Total number of different break types observed on mammal bones and teeth (Eb = excavation break; Db = dry break; Gb = green break); number of complete bones and tooth.

Breakage	Number
Eb	137
Db	263
Gb	73
Gb + Eb	21
Gb + Db	13
EB + Db	1
Db + Eb	8
Complete bones/teeth	31
Total	547

Table 6
Total number of human modifications on bones.

Human modification	Number	%
Green break	107	73,3
Cut marks	5	3,4
Percussion marks	13	8,2
Burning	18	12,3
Polished	4	2,7
Total	147	100

breakage were measured.

Most of the long bone diaphysis were small and lacked sufficient anatomical features for precise identification. To assess the potential for bone marrow extraction, long bone shafts were classified. However, in most cases, anatomical and taxonomic identification was not possible due to the fragmentary nature of the remains. Only seven shafts (3 humeri and 4 tibiae) could be anatomically classified (Table 7).

Of the bones with green fractures, 18.7 % (n = 20) retained their epiphyses. The data suggest that humeri, radii, tibiae, and metapodia (including both metacarpals and metatarsals) from ruminants and suids were deliberately fractured.

Percussion marks were identified on 13 bones (Table 6). In addition, two small splinters with well-developed bulbs of percussion and impact points were recovered.

The majority of bones with green breakage consisted of shaft fragments from medium-sized mammals (n = 92), while only 15 were derived from large mammals. This is consistent with the taxonomic profile, which is dominated by caprines and suids.

Regarding the length of the green break bones measured on 90 long bones (84.1 % of the total number of green break bones), their statistical analysis is illustrated in Fig. 7, were most bone length range between 20 mm and 40 mm. Measurements greater than 40 mm become less frequent. The skewness suggests the presence of a specific bone size, while longer bone is less common, indicating a standardization of bone size. This pattern suggests intensive opening of long bones to access the medullary cavity, thus inconsistent with the bone grease rendering pattern.

The remaining breakage categories, illustrated in Fig. 7, with Green break + Dry break category exhibiting a wider spread (interquartile range IQR 29–41 mm) than the Green break category (28–37 mm). The median value is 38 mm (horizontal line within the box), higher than that observed in the 34 mm Green break category. One outlier is present (the individual point above the upper whisker), with the maximum bone size of 73 mm. Green break + Excavation break category reveals a spread of bone size wider to the previous categories (IQR 23 mm to 39 mm). Median bone size is 29 mm.

In summary, the Green break + Dry break and Green break + Excavation break categories exhibit a wider distribution compared to the Green break category, which demonstrates a more compact distribution with overall smaller bone sizes. This suggests that some larger bones initially fractured as green breaks were subsequently affected by post-depositional processes at the site (e.g., erosion and historical occupation). The presence of outliers in the Green break category indicates variability in bone sizes and corresponds to measurements of large mammal long bones.

5. Discussion

As outlined in the previous section, anthropogenic fractures constituted the primary taphonomic evidence of human activity in the Neolithic Branqueiras assemblage, recorded exclusively on bones. These fractures were predominantly observed on the diaphysis of long bones, indicating the exploitation of bone marrow from medium and large-

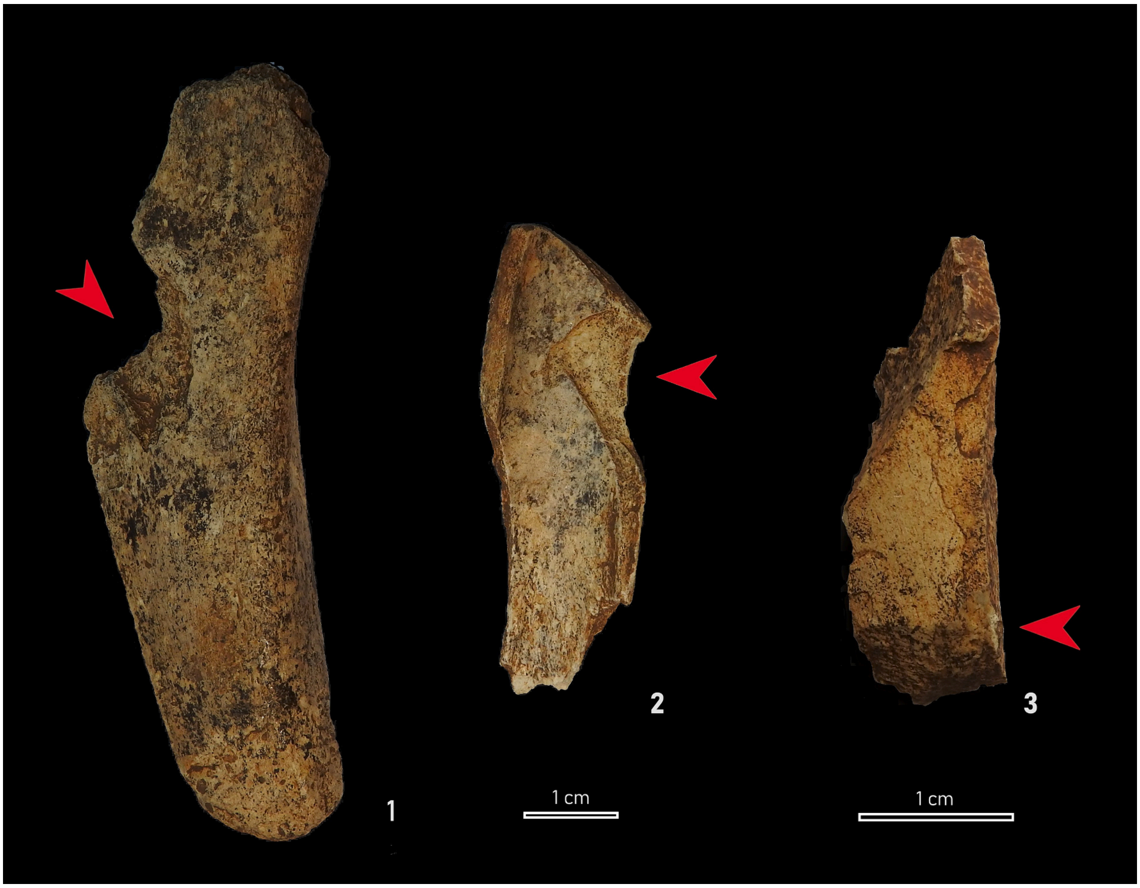

Fig. 3. Green break bones with percussion marks: 1 and 2. Splinter: 3. The red arrows indicate the percussion marks in 1 and 2 and the percussion point in 3.

sized mammals, a behaviour that is rare among other known sites from the same period in Portugal.

At Branqueiras, the relatively high occurrence of dry breakage due to post-depositional processes likely reduced the number of bones exhibiting green fractures, which may have originally been higher. Nonetheless, nearly 25 % of the assemblage provides clear evidence of bone marrow extraction from both ruminants and swine. Half of these bones measure between 30 and 40 mm in length, indicating intensive breakage of long bones, although some longer bones may have been present in the original assemblage. While few bones could be anatomically classified, the data suggest that humeri, radii, tibiae, and metapodia were utilised in the process, with no apparent selection for specific bones.

Different skeletal parts contain varying amounts of fat. Cancellous bone from epiphyses and axial bones are rich in fat (Lupo, 1998; Outram and Rowley-Conwy, 1998); however, their extraction requires more effort than marrow exploitation from long bones and mandibles (Outram and Rowley-Conwy 1998; Outram, 2001). In the present assemblage, there is no evidence of bone grease rendering since complete bones such as tarsals and phalanges were recovered intact, and the epiphyses of humeri, radii and metatarsals remained unbroken (Table 8). Additionally, spongy bones with green breakage or impact points are absent.

Helicoidal and curved fractures with smooth obtuse and acute angles to the transverse plane of the cortical surface of the bone associated with percussion marks, has been described in the literature as the result of the intentional opening of the medullary cavity of long bones to exploit the marrow content. The process of opening bones is achieved through flexion or percussion (e.g., Lyman, 2004, 2008; Outram, 2001, 2002, 2005; Bemilli, 2018). Moreover, marrow content from long bones varies between species and age (Outram and Rowley-Conwy 1998: 849; Christensen et al. 2018). Nevertheless, it is undeniable that the long bones of large mammals yield a higher quantity of fat than those of medium-sized mammals.

5.1. *Inter-site variability in the Western Iberian Neolithic*

One of the most significant conclusions that can be drawn from the Branqueiras data is the absence of comparable exploitation of bone marrow from medium and large-sized mammals in earlier, contemporaneous, or later prehistoric sites.

Indeed, Early Neolithic caves such as Nossa Senhora das Lapas and Cadaval, in the Estremadura province, which were used as necropolises, were dominated by leporids (Almeida et al., 2022) but evidence of the intentional opening of long bone cavities in bovids was detected at the former site whereas at Cadaval, percussion marks were observed on caprines, cattle, and suids, though in very small percentages, less than 0.5 % (Almeida et al., 2015). However, even in habitat open air sites, such as Encosta de Sant'Ana in Lisbon (Angelucci et al., 2004, Leitão et al., 2021) only 5 bones up to 424 were assigned to have been intentionally broken (Almeida et al., 2017).

Late Neolithic and Chalcolithic ditched enclosures in the Alentejo province of Southern Portugal, such as Perdigões, Montoito 2, and Barranco do Xacafre, exhibit few anthropogenic marks on bones, suggesting minimal bone marrow exploitation (Aleixo, 2024; Costa, 2010, 2013, 2018; Costa and Mataloto, 2017; Mata Vivar et al., 2022; Milesi García et al., 2022). Regarding the Porto Torrão ditched enclosure, layers dated to the Late Neolithic yielded 22 % green breakage (unpublished data), in parallel with Branqueiras. However, the circumstances remain unclear, as the assemblage is still under study. Similarly, in the Chalcolithic walled enclosure of Castanheiro do Vento in northern Portugal, green fractures are also extremely rare (Costa, 2016, and unpublished data). At the Middle Bronze Age site of Montinhos 6 in

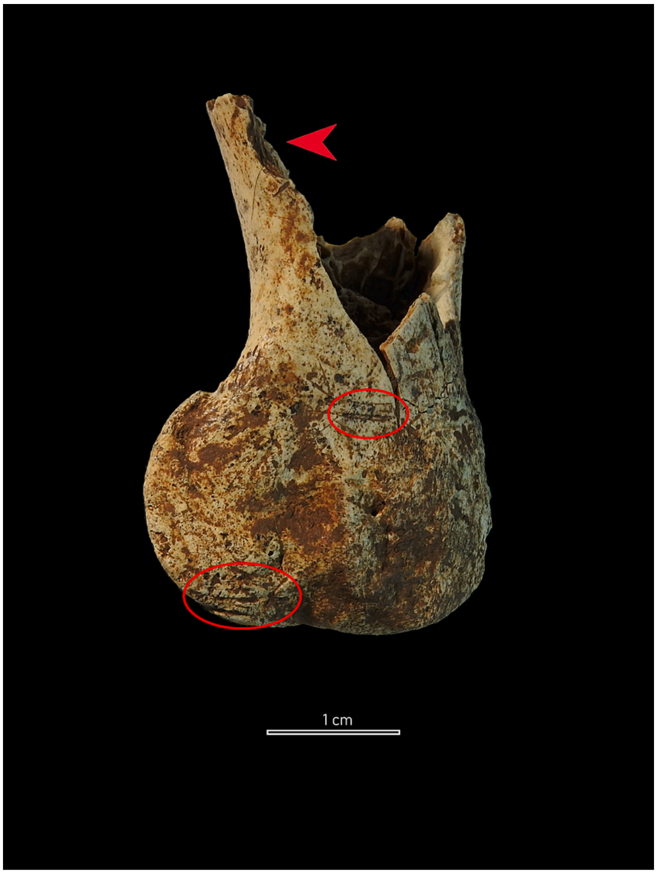

Fig. 4. Sheep humerus with percussion mark (red arrow) and cut marks (red circles).

Southern Portugal (first half of the second millennium BC), intentional opening of long bones was also rare, comprising approximately 3 % of the total faunal assemblage (Costa, 2013) (Fig. 1; Table 9).

At the coeval open-air, short-term settlement of Los Barruecos, on the Spanish side of the middle Tagus basin, 388 bones and teeth were recovered, but only 8 bovid and medium-sized mammal long bones exhibited anthropogenic breakage (Almeida et al., 2021) (Table 9). This highlights the need for further research on bone fat exploitation at other sites in this region and in this time period.

5.2. Hypothesising a response to environmental stress

Radiocarbon dating of Branqueiras partially coincides with the hiatus observed at the Leceia settlement between its Late Neolithic (layer 4) and Initial Chalcolithic (layer 3) occupations. The authors estimate a hiatus of 30 to 150 years based on a total number of 18 determinations (Soares and Cardoso, 1995) but do not provide any explanation for the fact. At this site, there is a direct contact between both layers, each with material culture typical of the corresponding periods and the setting up of a walled enclosure and the onset of the copper metallurgy in the latter period. Consequently, the site was abandoned during a brief interval that coincided with significant cultural transformations.

At a regional scale, sites rarely present a clear, well-established Late Neolithic/Initial Chalcolithic sequence, the main examples being Parede (Serrão, 1983), Leceia (Cardoso, 2004) and Penedo do Lexim (Sousa, 2021). Conversely, at the beginning of the Chalcolithic period, a remarkable increase in the number of sites built "*ex novo*" is now documented, particularly on elevated locations, like Leceia—a fact that probably explains its reoccupation. This change in human settlement has been suggested, by various scholars (e.g., Cardoso, 2004), as the result of a demographic increase, driven by the full implementation of the so-called "secondary products revolution" associated to greater social complexity. Thus, a cultural explanation. Alternatively, it's conceivable that the interruption in human occupation coincided with resource limitations, potentially driven by environmental changes.

There is a notable lack of paleoenvironmental data with high chronological resolution at a regional scale across Iberia. However, isotopic records from stalagmites in Buraca Gloriosa Cave, approximately 130 km North of Branqueiras, indicate drier conditions *ca.* 5 ka BP (~2950 cal BC) (Thatcher et al., 2020: 977). A marine core analysing pollen data off the coast of Lisbon reports a similar drying trend after *ca.* 5 ka BP (~ 2950 cal BC), with an increase in anthropogenic presence despite the low resolution of the record after this date (Chabaud et al., 2014). Another pollen record from southern Portugal (Algarve region) indicates a drying episode after *ca.* 5 ka BP (~ 2950 cal BC), where a *Quercus* forest, reflective of a warmer, moist oceanic climate, transitions to an expansion of shrublands indicative of a drier climatic regime and increasing anthropogenic activity (Fletcher et al., 2009). Hydrological proxies based on CT scans of stalagmites from caves in Southern Spain reveal a similar drying trend, with the establishment of a more Mediterranean climate in Southern Iberia around 5.3 ka BP (~3350 cal BC), correlating with a decrease in Northern Hemisphere insolation (Walczak et al., 2015: 118). It should be noted, however, that regional variations in the onset of the Mediterranean climate in Iberia may occur, given the complex topography, topoclimatology, and biomes (Walczak et al., 2015; Thatcher et al., 2020).

Under an arid phase, the scarcity of pastures may have led to a

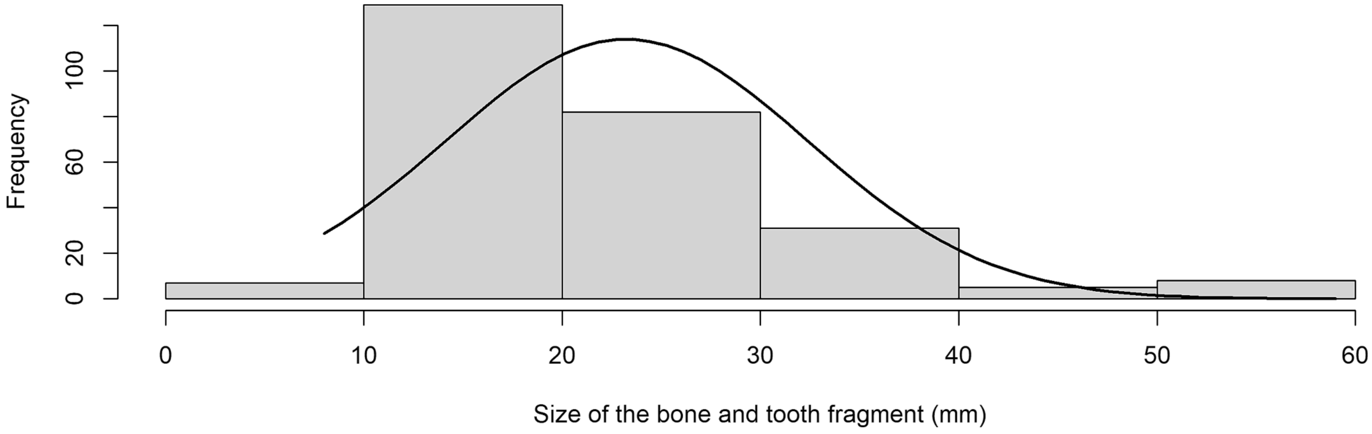

Fig. 5. Histogram of dry breaks measurements including bones and teeth.

Fig. 6. Image of shafts with green breakage categories: green break + dry break type: 1 and 4 (red arrow points to dry break surface); green break type: 2; green break + excavation break type: 3 and 5 (excavation break in red squares). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 7
Total bones with green break per taxon, per middle size mammal (MSM) and large size mammal (LSM).

	***Sus* sp.**	***Cervus Elaphus***	***Bos taurus***	***Ovis aries***	***Ovis/ Capra***	**MSM**	**LSM**	**Total**
Humerus	1		2	1	1	3		8
Radius	2							2
Metacarpal		3						3
Tibia	1					2	2	5
Metatarsal					2			2
Unidentified shafts						79	8	87
Total	4	3	2	1	3	84	10	107

decline in cattle populations (whose exploitation is usually more linked to long-term settlements) along with an increase in caprines (i.e., sheep and goat) usually associated to more mobile human groups. And certainly, this is exactly what is observed in the comparison of faunal assemblage from layer 4 (Late Neolithic) at Leceia (Cardoso and Detry, 2001/2002) and Branqueiras (Fig. 8).

Despite the difference between the samples under study in terms of NISP (Branqueiras: n = 125; Leceia: n = 733), there are some notable differences: i) the aforementioned opposition between the frequencies of cattle (higher in Leceia) and sheep/goats (more frequent in

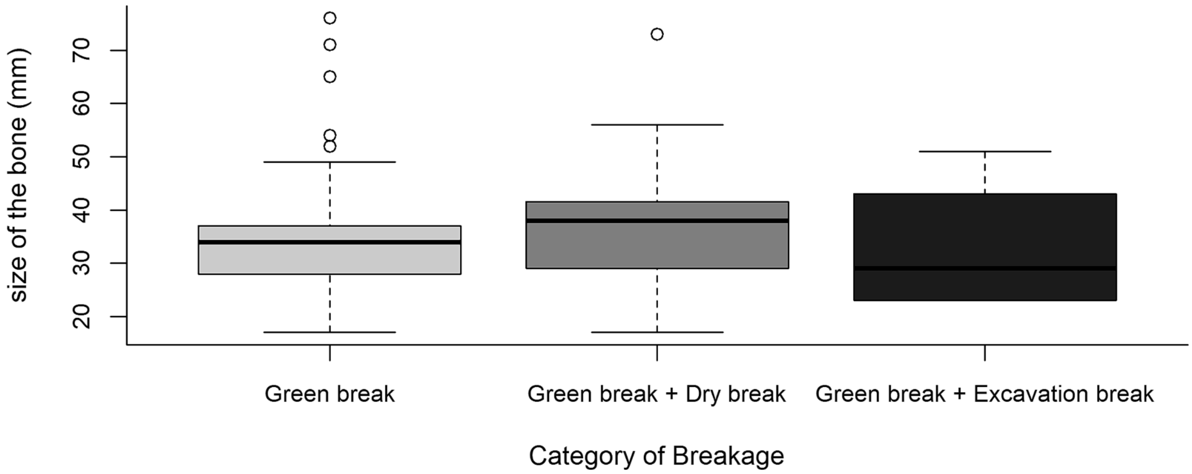

Fig. 7. Boxplot representing size of bone green breaks in the three categories observed.

Table 8
Complete bones (CB) and complete epiphysis (CE).

	Sus sp.		Ovis/ Capra	Ovis aries	Bos taurus	
	CB	CE	CB	CE	CB	CE
Distal humerus		1		1		
Proximal radius		2				
Astragalus	1		1			
Proximal metapodium		2				
Distal metapodium						1
Unfused metapodium condyle	1					
Phalanges	6				1	
Total	8	5	1	1	1	1

Branqueiras); ii) although we cannot quantify the real frequency of wild and domestic suids, data reveals a the clear dominance of this genus at both sites opening up the possibility of being wild animals; and iii) indirectly proving this hypothesis, there is indeed an increase in hunted species at Branqueiras, as illustrated in the frequency of red deer and leporids when compared with Leceia (exclusively rabbits in both sites).

We propose that the Branqueiras site represents an occupation during a brief cultural transitional period. During this time, itinerant groups inhabited low-lying coastal areas, in contrast to the hilltop, long-term settlement at Leceia. These groups accessed diverse biomes and exploited a broader spectrum of wild resources. Both Branqueiras and Leceia are situated within the same ecological and geographical environment, highlighting the importance of direct comparison between the two sites. Consequently, the resources identified at Branqueiras (as summarized in Table 3), including those derived from agriculture and the gathering of wild edible plants, were also present at Leceia. However, ichthyological (Antunes and Cardoso, 1995), malacological (Guerreiro and Cardoso, 2001/02), and avian (Gourichon and Cardoso, 1995) resources, while present in Layer 4 at Leceia, occur in proportionally smaller frequencies than at Branqueiras.

Coincidently, a recently-published study on the grazing strategies of domestic mammals of Leceia concluded for “[…] a slight impoverishment of the values of δ^{13}C and δ^{15}N is observed in layer 3 (Initial Chalcolithic) when compared to layer 4 (Late Neolithic), probably associated with two factors: a change in climate and environmental conditions and consequently to a change in plants available for animal consumption; and a change in grazing zones” (Navarrete et al., 2024: 244; original in Portuguese). This further reinforces the possibility put forward in this paper of a climatic event taking place at the end of the Late Neolithic and triggering the observed changes in human settlement and economics at the Neolithic-Chalcolithic passage.

In this context, the intensification of bone marrow exploitation during the climatic transition may have provided significant source of additional nutrients, a role previously overlooked. According to the available data, the importance of bone marrow exploitation diminished during the Chalcolithic and later periods, when the consumption of dairy products became more prominent (e.g., Johnson et al., 2018; Smyth et al., 2023), a strategy that seems to be at place also in the Chalcolithic of our study area (Cardoso and Detry, 2001/2002; Valente and Carvalho, 2014).

Table 9
List of sites with information of anthropogenic breakage from Early Neolithic to Bronze Age in Western Iberia. Letters and numbers in the 1st column are the reference of the sites in the Fig. 1.

Map/number	Site/municipality	Region	Chronology	% of green break	Reference
B, 1	Branqueiras (Cascais)	Estremadura	Late Neolithic	24.4	This paper
B, 2	Leceia (Oeiras)	Estremadura	Late Neolithic and Chalcolithic	No data available	
B, 3	Encosta de Sant’Ana (Lisbon)	Estremadura	Early Neolithic	0.7	Almeida et al. (2017)
A, 2	Nossa Senhora das Lapas (Tomar)	Estremadura	Early Neolithic	<0.2	Almeida et al. (2015)
A, 3	Cadaval Cave (Tomar)	Estremadura	Early Neolithic	<0.5	Almeida et al. (2015)
A, 4	Los Barruecos (Malpartida de Cáceres)	Spanish Extremadura	Early Neolithic	2	Almeida et al. (2021)
A, 6	Perdigões (Reguengos de Monsaraz)	Alentejo	Late Neolithic	3	Costa (2018)
A, 6	Perdigões (Reguengos de Monsaraz)	Alentejo	Chalcolithic	AVG = 8.3	Costa (2010, 2013)
A, 7	Porto Torrão (Ferreira do Alentejo)	Alentejo	Late Neolithic	22	Unpublished data
A, 8	Barranco do Xacafre (Ferreira do Alentejo)	Alentejo	Late Neolithic	1,5	Aleixo (2024)
A, 1	Castanheiro do Vento (Vila Nova de Foz Côa)	Douro Valley	Chalcolithic	0,7	Costa (2016 and this paper)
A, 5	Montoito 2 (Redondo)	Alentejo	Chalcolithic	3	Costa and Mataloto (2017)
A, 9	Montinhos 6 (Serpa)	Alentejo	Bronze Age	3	Costa (2013)

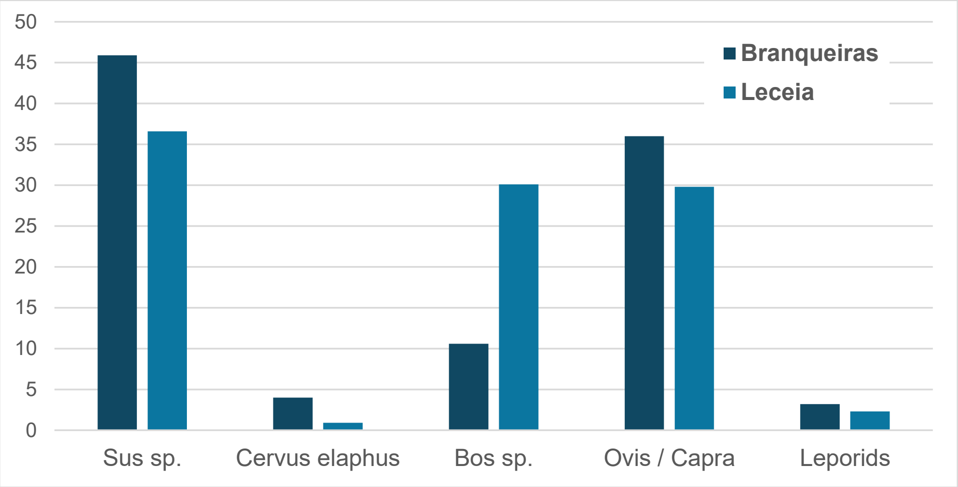

Fig. 8. Relative comparison of main mammal taxa between Branqueiras (see Table 2) and layer 4 at Leceia (Cardoso and Detry, 2001/02) in percentage of NISP.

6. Conclusion

The mammal assemblage from the Branqueiras archaeological site clearly reveals the importance of bone marrow exploitation to a degree not observed at any other site from the same period in Western Iberia. Located on the Western Atlantic cost, Branqueiras shows evidence of a short-term occupation from 2900 to 2700 cal BC, coinciding with the local Late Neolithic cultural period. This occupation aligns with a hiatus identified at Leceia, a hilltop site in the same region, and with a period of climate change characterised by reduced annual precipitation, hot and dry Summers, and cold Winters.

Despite Leceia having access to the same biome as Branqueiras, this arid climatic phase may have driven human adaptation, marked by the occupation of low-lying coastal areas by itinerant groups. These groups primarily exploited domestic caprines and swine, hunted small and large game such as rabbits and red deer, and had direct access to shellfish.

In this context of intense exploitation of animal resources, likely driven by a decline in agricultural practices and cattle herding due to climate change, the consumption of bone marrow provided a vital source of fat and nutrients, essential for the group's subsistence. A definitive understanding of the processes at play in Branqueiras will necessarily depend on a re-analysis of the faunal material from layers 3 and 4 at Leceia to identify patterns and quantify the extraction of bone marrow during the Late Neolithic and Chalcolithic periods at the site.

The available published data on bone marrow exploitation patterns is limited and biased towards hunter-gatherer societies. In this context, the present study offers insight into human adaptation to climate stress conditions within fully established prehistoric farming systems.

CRediT authorship contribution statement

Cláudia Costa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Maria João Fernandes Martins:** Writing – original draft, Formal analysis. **Vera Cardoso:** Visualization. **Guilherme Cardoso:** Visualization. **António Faustino Carvalho:** Writing – review & editing, Writing – original draft, Conceptualization.

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Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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