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Warmed to the bone. A zooarchaeological and metallurgical approach to calcined bones in Iberian Iron Age metalworking. The case of A Cividá (Cerdedo-Cotobade, Galicia)

Samuel Nión-Álvarez

samuel.nion-alvarez@incipit-csic.es

INCIPIT – CSIC

Clara Veiga-Rilo

Universidade de Santiago de Compostela

Hugo Bal-García

Universidade de Santiago de Compostela

Elena Taboada Durán

Arbore Arqueoloxía e Restauración S. Coop. Galega

Research Article

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Abstract

This paper investigates an unusual assemblage of calcined animal bones recovered from an Iron Age metalworking context at the hillfort of A Cividá (Cerdedo-Cotobade, Galicia, Spain). The presence of a large quantity of thermally altered bone in an area associated with bronze production raises the question of whether these remains were deliberately incorporated into the metallurgical process. A Cividá therefore provides an unusual opportunity to investigate the presence of animal bones in Iron Age bronze-working contexts and their functional and symbolic significance.

This work adopts a multidisciplinary approach that combines archaeological contextual analysis with zooarchaeological and archaeometallurgical analyses. Particular attention is paid to the thermal alteration of the bones, their taxonomic and anatomical composition, as well as their elemental composition, as assessed by portable X-ray fluorescence (pXRF). These lines of evidence are used to evaluate possible explanations for the presence of the bones and to assess their potential technical role within the metallurgical sequence.

Introduction

Research into Iron Age metallurgy has seen considerable development in recent decades (Dubreucq 2013; Pare 2025), largely as a result of notable technical advances and interdisciplinary approaches. The identification of numerous trade networks, technical processes and production strategies (Kostoglu 2005; Brauns et al. 2013) has greatly expanded our understanding of the discipline. Concurrently, recent research has examined the relationship between ritual, symbolism and metal production (Kuijpers 2018; Stepanov et al. 2022). Together, these research trends have established symbolism as an intrinsic part of metalworking (Killick 2004; Dobres 2010), demonstrating that techniques and rituals are essential components of metallurgical practices and accessible to archaeological analysis.

This study analyses a metal production context containing an unusually large quantity of calcined bones. Located at the hillfort of A Cividá (Cerdedo-Cotobade, Galicia, Spain) (Fig. 1), the site provides an excellent opportunity to investigate the relationship between these faunal remains and bronze-working. The A Cividá context is a particularly noteworthy case study: it provides an informative bronze-production material sequence with a significant number of bones, which are usually poorly preserved in NW Iberian archaeology due to the high acidity of local soils (Fernández Marcos et al., 1994). The presence of these unexpected bones raises the question of whether they are an incidental finding or were deliberately incorporated into the metalworking process. By combining zooarchaeological, taphonomic and archaeometallurgical analyses with archaeological contextual analysis, this study evaluates the relationship between these calcined bones and the metallurgical activities documented at A Cividá.

Metalworking in NW Iberian Iron Age: Traditions, Symbolism, and New Approaches

Research into Iron Age metallurgy is a long-established tradition along the Atlantic coast of the Iberian Peninsula (Monteagudo García 1977; Rovira Llorens et al. 1997), reflecting the substantial metallurgical activity documented across the region, including bronze production and circulation (Comendador Rey 1999; Armada and Martinón-Torres, 2016) and goldsmithing (Perea 2000; Ladra 2020). Research has focused mainly on manufacturing (Comendador Rey 1999), large-scale interaction dynamics (Comendador Rey, 2003; Armada & García-Vuelta 2021) and the role of metallurgy and blacksmiths in Iron Age social structures (Sastre 2001, p. 77; González-Ruibal, 2006-7, p. 417–421).

Metallurgy in Iron Age NW Iberia was characterised by the coexistence of bronze, iron and gold, with distinct functions and uses. Gold remained primarily associated with ornamental and prestige objects (Ladra 2020), alongisde diversification in production techniques (Armbruster and Perea, 2000, p. 109). Gold production increased significantly in the Late Iron Age (Armada & García-Vuelta 2021), when gold artefacts increasingly concentrated in large *oppida* along the Atlantic coast (Nión-Álvarez 2022). The earliest evidence of iron production dates back to the 7th century BCE (Peña Santos 1992), but it did not become widespread in NW Iberia until the 5th century BCE (Camino Mayor & Villa Valdés 2014, p. 65). Pollution records indicate particularly intense metallurgical activity during the Late Iron Age, accompanied by a significant transformation of the social landscape (Silva-Sánchez and Armada, 2023). Metalworking also became associated with liminal or peripheral areas, sometimes beyond settlement boundaries (González-Ruibal 2006-7, p. 496), partly due to the greater technical complexity of iron production. However, it remained seasonal, with smiths also participating in subsistence activities (Giles 2007, p. 398). Workshops included several furnaces for processing raw materials and producing wrought iron, as well as areas for forging and finishing objects (Fernández-Posse and Sánchez-Palencia 1988; Gómez Filgueiras de Brage 2003). From the 4th century BCE onwards, iron predominated in utilitarian artefacts, particularly tools and weapons, including new implements such as tongs, picks and a wide range of agricultural tools (Romero Masiá 1992, p. 158–163; González-Ruibal 2006-7, p. 500).

Bronze objects were commonly produced using lead-rich ternary alloys, reflecting some continuities with the Late Bronze Age (LBA) (Armada Pita et al. 2008). However, the social uses of bronze changed during the Early Iron Age (EIA) (Armada et al. 2023). Weapons and objects of personal ostentation (González García 2009) were eventually replaced by votive deposits consisting primarily of palstave axes. Dedicated production areas were largely absent from LBA and EIA settlements, but specialised workshops and craft-production areas emerged between the 6th and 5th centuries BCE, as documented in Punta de Muros. This site suggests that large domestic compounds and the control of metal production were associated with changes in settlement organisation and social differentiation (Nión-Álvarez and González García 2023, p. 66). In the Late Iron Age, bronze remained widely used, with similar production techniques but an increasing emphasis on purpose-specific tools and ritual objects such as *situlae* and sacrificial bronzes (Armada Pita 2003). Bronze weapons persisted, although some, such as antenna daggers, combined bronze hilts with iron blades (Rodríguez Cao 1993).

The symbolic dimensions of metalworking in NW Iberia have recently received increasing attention (Nión-Álvarez 2022; Nión-Álvarez and Veiga-Rilo, 2025), building on research from Scandinavia (Haaland

2004; Barndon 2005) and the British Isles (Hingley 1997; Dolan 2016). However, similar attention is needed for other metallurgical practices, including bronze production. Although iron metalworking involves stricter procedures and is embedded in a complex techno-symbolic network (Childs and Herbert, 2005), ritual processes associated with bronze production have also been documented, particularly in relation to smelting practices (Alberghina 2023). Metalworking cannot be understood solely as a technical procedure, as it is intertwined with a complex network of intangible agents and cultural expressions (Childs 1999), because any technological activity of the past required a symbolic justification (Ingold 2000, p. 316). Many aspects now interpreted through the lens of science and technology were previously framed through alternative worldviews and systems of knowledge (Pfaffenberger 1988, p. 236): mythology, imagery and the environment shaped how the world was classified through the “science of the concrete” (Lévi-Strauss 1988, p. 12–14). Technique and symbolism were part of the same reality (Dobres 2010, p. 110), where the synergy of technical, esoteric and symbolic procedures helped define the blacksmith as a specialist (Kuijpers 2018, p. 565). Examining these less visible dimensions of metallurgical practice may therefore reveal material evidence that would otherwise remain archaeologically overlooked.

Case study: A Cividá (Cerdedo-Cotobade)

A Cividá is an Iron Age hillfort located on top of a low hill overlooking the valley carved by the River Lérez (Fig. 2). It is defined by an acropolis surrounded by a 5-metre-high rampart and a terrace on the north side. The site covers an inhabited area of 1.7 hectares, slightly above average for settlements in the region (Carballo Arceo 2002). A concentration of rock carvings lies outside the southern wall. Although no absolute dates are currently available, the material assemblage clearly points to an Iron Age occupation, with only limited evidence of Roman material culture, restricted to abandonment contexts following the final occupation of the hillfort.

The site has been investigated in two archaeological campaigns directed by Benito Vilas and Elena Taboada (2024 and 2025, respectively). Two excavation areas were opened in different sectors of the site: S2 in the central part of the hillfort and S1 in the access area. Survey S2, measuring 5x5 metres, was associated with domestic occupation, including a dwelling structure and abundant evidence attributable to the Iron Age (Taboada Durán 2025). Survey S1 measured 8x5m and was located in the entrance area. In this sector, part of the access system, a section of the defensive wall, and a terracing system designed to facilitate movement across the naturally sloping terrain were documented. The context examined in this study is located in Survey S1, specifically in the western part of the entrance area. The area is delimited by a small curved wall facing the entrance (UE115). Stratigraphic analysis identified successive episodes of collapse and abandonment that gradually filled this structure.

The associated occupation deposits (UE116 and UE117), corresponding to the main occupational phase of the site, indicate a metalworking area (Fig. 3), most likely involved in bronze production (Fig. 4). The association of a small fired-clay hearth, slags (although not particularly abundant) and crucibles bearing bronze-related scorification provides independent evidence for metalworking in this area (Fig. 5). The

location of the workshop on the outskirts of the hillfort is also consistent with the spatial organisation of Iron Age metalworking areas (Nión-Álvarez 2022, p. 497). More than 800 fragments of calcined bones were also recovered from the hearth. As mentioned, their presence is unusual in this context, not only because bones are usually poorly preserved, but also because they are not abundant in metalworking contexts (with only a few exceptions such as Nión-Álvarez and Veiga-Rilo 2025). This study therefore evaluates whether the assemblage is related to metalworking activities and, if this is supported, their potential function within the metallurgical process.

Materials and Methods

This study presents a multifactorial analysis of the bone remains recovered from the metallurgical hearth at A Cividá, examining their depositional, taphonomic and elemental characteristics and their relationship with metalworking.

Taphonomic and thermal analysis of the bone sample

The bone assemblage was recovered from Survey 1, stratigraphic unit 117, an intramural deposit of thermally altered yellowish sediment containing charcoal, calcined bone remains, and ceramic fragments, including crucibles (Taboada Durán 2025). Excavation was conducted manually using fine dental tools. Following recovery, the specimens were stored without cleaning or post-excavation treatments. The assemblage was processed following the protocol developed by Nión-Álvarez and Veiga-Rilo (2025) for bones from metalworking workshops. All fragments were dry-cleaned with soft-bristled brushes before macroscopic examination.

Anatomical and taxonomic identification was based on a reference collection, comparative anatomy and zooarchaeological manuals (Schmid 1972; Davis 1987; Hillson 1992; Cohen & Serjeantson 1996; Beisaw 2013). Remains were identified to the lowest possible taxonomic level; specimens that could not be assigned more specifically were classified by body-size category (e.g. species, genus, family, etc.) (Brain 1981; Marean et al. 2000): Size 1 (< 20 kg), Size 2 (18–100 kg), Size 3 (70–300 kg), Size 4 (300-1,000 kg) and Size 5 (> 1,000 kg). Orders (e.g. ungulates, carnivores, lagomorphs) were distinguished where possible.

The assemblage was quantified using Number of Remains (NR), as extensive fragmentation precluded reliable estimates of Minimum Number of Elements (MNE) and Minimum Number of Individuals (MNI) (Lyman 2008). Taphonomic analysis combined macroscopic inspection and examination under an Olympus SD-51 stereomicroscope at up to 40X magnification. All remains were assessed for anthropogenic modifications, carnivore activity, and diagenetic alterations (Villa and Mahieu 1991; Lyman 1994; Fisher 1995; Fernández-Jalvo and Andrews 2016; Gifford-González 2018).

Thermal colouration was classified according to Stiner et al. (1995). Stiner's Grade 6 was subdivided into 4 observable colour groups based on thermal exposure following Ellingham and Thompson (2015)

(Table 1). Other thermal alterations, including morphological changes, size reduction and potential changes in fragmentation patterns (Spennemann and Colley 1989; Imaizumi 2015; Nikita 2021; Sala et al. 2026), were assessed.

Table 1
Colouration-Temperature. Subcategories within Grade 6 of Stiner's (1995) colouration criteria, modified according to the temperature assignments proposed by Ellingham and Thompson (2015).

Grade	Colour description
6 – 1	White/grey with blue patches
6 – 2	Milky-white with blue patches
6 – 3	Milky white with dark spots
6 – 4	Milky white

Portable X-Ray Fluorescence Spectometry

Elemental composition analysis was carried out on 12 bone fragments representing the different colour groups described above. The aim was to chemically characterise the bone remains and determine whether the elemental composition is consistent with metallurgical exposure and, if so, assess the processes potentially involved. The analysis was carried out using an Olympus (now Evident) Vanta M portable X-ray fluorescence spectrometer (pXRF) mounted on a fixed workstation at the Instituto de Ciencias del Patrimonio of the Consejo Superior de Investigaciones Científicas (INCIPIT-CSIC), Santiago de Compostela, Spain. Data acquisition used the *GeoChem* method, which applies three consecutive measurements at the same analytical spot to optimise detection of different elements: the first measurement targets major elements (40 kV, 56 µA, 2000 µm aluminium filter, 30 s), the second targets light elements (10 kV, 67 µA, no filter, 30 s), and the third targets heavier elements (50 kV, 56 µA, 350 µm copper filter, 30 s). This method is optimised for the analysis of mineral elements. The resulting data are elemental concentrations expressed in parts per million (ppm), as reported by the *Vanta Desktop App* software.

Statistical analysis

XRF data were statistically analysed to assess elemental distributions in the bones and their relationship to the metallurgical process. Statistical analyses were performed using RStudio (version 2026.07.1). Prior to analysis, values below the limit of detection (LOD) obtained by pXRF were treated as missing values (*NA*), and elements with more than 50% of measurements below the LOD were excluded from multivariate analyses.

Descriptive statistics (mean, median, standard deviation, coefficient of variation, minimum, maximum, interquartile range, skewness, and kurtosis) were calculated for all variables. To minimise the influence of variations in bone mineral content and surface-related effects inherent to in situ pXRF measurements, elemental abundances were additionally expressed as X/Ca ratios (Dunlea et al. 2020).

Relationships among variables were evaluated using Spearman's rank correlation coefficient (ρ), with statistical significance set at $p < 0.05$. Multivariate patterns were explored by Principal Component Analysis (PCA) using standardised variables (mean = 0, standard deviation = 1). Hierarchical Cluster Analysis (HCA) was performed on the same variables using Euclidean distance and Ward's minimum variance method (Ward.D2). The resulting dendrogram was used to compare element clustering patterns with those identified by the PCA.

Results

Bone sample

The faunal assemblage recovered at the site consists of 818 bone remains, with no teeth, antlers/horns or shells identified. The assemblage is highly fragmented, with remains ranging from 4.4 to 37.7 mm and a mean length of 14.2 mm. The bones are also light, ranging from 0.1 to 6.3 g, with a mean of 0.4 g per fragment and a total mass of 286.9 g. Accordingly, both the anatomical (4.2%) and taxonomic (2.8%) identification rates are low.

The assemblage is dominated by indeterminate bone remains (n = 422; 51.6%). A substantial proportion of the assemblage could nevertheless be classified as flat, articular and long bone shaft fragments. Within this group, flat bone fragments clearly dominate (n = 334), including a small number of specimens attributable to cranial elements (n = 7), ribs (n = 4), vertebrae (n = 2) and a single mandibular fragment. Although much less numerous, fragments of articular bone surfaces (n = 26), long bones (n = 19) and isolated trabecular bone tissue (n = 17) were also identified.

Taxonomic identification was not possible for most of the assemblage. A single metatarsal fragment was attributable to the Ovis/Capra group, although it could not be confidently assigned to either species. Body size could be established for 23 bone fragments, with a clear predominance of Size 2 animals (n = 20), compared with two Size 1 and one Size 3 specimens. However, 97.2% of the assemblage could not be taxonomically assessed, severely limiting interpretation.

Bone surface modifications revealed a relatively homogeneous taphonomic profile. The remains are generally well preserved, with largely intact cortical surfaces, but show extensive cracking and predominantly white colouration (Stiner Grade 6), consistent with exposure to high temperatures (> 600°C). Almost all specimens also exhibit small greyish-black spots identified as adhering charcoal particles under magnification. No anthropogenic modifications other than thermal alteration (e.g. cut or percussion marks), or traces of other biotic agents (e.g. carnivores, rodents or root etching), were identified, providing little evidence for reconstructing carcass processing.

All fractures correspond to dry-bone breakage according to the criteria established by Villa and Mahieu (1991). These fractures are parallel to the bone's longer axis, display right-angle fracture planes and have a markedly irregular texture, consistent with deterioration of the collagen fibres and loss of bone resistance and elasticity before breakage.

Despite the challenges of identification and interpretation, the faunal assemblage helps elucidate the relationship between Iron Age hillfort inhabitants and animal resources in NW Iberia. In this region, highly acidic soils severely limit the preservation of pre-Roman faunal remains (Fernández-Rodríguez 2010). Therefore, zooarchaeological research has often focused on specific depositional contexts, particularly shellmiddens, where the high concentration of calcium carbonate from mollusc shells promotes bone preservation (Estévez et al. 2013). Regional assemblages are dominated by domestic livestock, particularly ovicaprids, while cattle generally provide the greatest meat contribution (Fernández-Rodríguez 2003). The limited taxonomic evidence from A Cividá is compatible with the regional predominance of domestic livestock, and the predominance of Size 2 animals among unidentified remains may likewise indicate these taxa. However, the low identification rate prevents a meaningful assessment of the assemblage's faunal composition.

In any case, the high proportion of unidentified remains means that these interpretations must be treated with caution. Moreover, the faunal assemblages discussed above derive from domestic contexts where the remains were usually interpreted as food waste. By contrast, the assemblage from A Cividá originates from a highly specific metallurgical context, where the faunal remains may not have been intended for consumption and may have followed different patterns of use and deposition. The composition of the remains at A Cividá is exclusively mammalian, without any malacological or ichthyological remains, which are frequently represented in faunal deposits from Galician hillforts (González Gómez de Agüero et al. 2019).

Furthermore, both the nature of the deposit and its preservation processes differ substantially. Unlike most NW Iberian Iron Age bone records, the preservation of the A Cividá faunal remains is largely attributable to calcination, which is highly anomalous in the region. Calcination induces a series of chemical changes in bone structure, including the complete loss of the organic component and the recrystallisation of hydroxyapatite crystals, effectively mineralising the specimens and greatly enhancing their resistance to post-depositional degradation (Stiner et al. 1995; Shehata and Krap, 2024; Williams et al. 2025).

The small quantity of faunal remains recovered (< 300 g) may be explained by several factors. First, preservation depended on advanced calcination, so some specimens may not have been exposed to sufficiently high temperatures. This could reflect either their position within the fire or differences in the thermal resistance of skeletal tissues, as anatomical elements vary in their susceptibility to heat alteration (Spennemann and Colley 1989; Théry-Parisot et al. 2010; Imaizumi 2015; Nikita 2021). Any remains that did not undergo calcination would therefore be unlikely to survive in the highly acidic soil.

The assemblage may also have undergone treatment before or after burning. The absence of teeth is particularly noteworthy, given their high resistance to heat. Small skeletal elements, including phalanges, carpals/tarsals and patellae, are also underrepresented. This may simply reflect their lower cortical bone density and higher proportion of trabecular tissue, making them more susceptible to thermal degradation (Nikita 2021). Alternatively, their absence could result from cleaning the combustion feature after use or from anatomical profiles inherited from earlier processing and destruction of part of the skeleton, although this is difficult to reconcile with the selective absence of some of the smallest and most easily overlooked bones. However, given the limited anatomical information and the absence of taphonomic modifications (e.g. cut marks or intentional bone breakage) indicative of previous processing, this issue cannot currently be explored further.

XRF and statistical analysis

The dataset used for statistical analyses, after excluding elements with > 50% of measurements below the LOD, comprised LE, Ca, P, Al, Si, Mn, Fe, Sr, Cu, Ba, Pb, Zn, Cd, Ni, Zr, Rb, Th, Ti, As, W, Cr and Hg. Sn was excluded because 67% of measurements fell below the LOD, along with Ce, Y, Nd, Pr, Sb and U.

Descriptive statistics showed that LE, Ca and P were the dominant elements, displaying low coefficients of variation and near-symmetrical distributions (Supplementary Material – Descriptive statistics), consistent with the expected composition of bone bioapatite. By contrast, Al, Si, Fe and Mn exhibited greater variability, with Mn showing the strongest positive skewness. Cu and Pb displayed the highest coefficients of variation together with markedly elevated skewness and kurtosis, with elevated values concentrated in a small number of specimens.

Normalisation to Ca highlighted differences in elemental behaviour relative to the bone mineral fraction (Supplementary Material – Calcium ratio). The P/Ca and Sr/Ca ratios remained homogeneous throughout the assemblage, whereas Al/Ca and Si/Ca increased progressively from the Grade 6 – 2 to the Grade 6 – 4 colour group. Mn/Ca was highest in all Grade 6 – 4 specimens, while Cu/Ca and Pb/Ca showed the highest values, particularly in sample 3.I9. Sample 4.I10 also displayed elevated Cu/Ca values.

Spearman's rank correlation analysis (Fig. 6) revealed strong negative correlations between Ca and Fe, Al, Si and Zn ($\rho = -0.70$ to -0.87), whereas Al, Si and Fe formed a strongly correlated group ($\rho = 0.83$–0.84). Mn was positively associated with Al and Zn, and the Fe/Ca, Al/Ca and Si/Ca ratios were strongly correlated both with one another and with their corresponding elemental concentrations. Other notable associations included positive correlations between Rb and Zr ($\rho = 0.87$) and between Cr and As ($\rho = 0.80$), together with strong negative correlations between LE and Ca ($\rho = -0.85$) and between Hg and W ($\rho = -1.00$).

PCA identified three principal components accounting for 63% of the total variance (PC1 = 30%, PC2 = 17% and PC3 = 16%). Subsequent components were not interpreted because each accounted for less

than 10% of the variance and lacked a clear geochemical meaning (see Fig. 7). PC1 separated specimens enriched in Ca, P and Sr from those enriched in Al, Fe, Si, Mn and Zn. Accordingly, specimens in the Grade 6 – 2 colour group displayed predominantly positive PC1 scores, whereas those from Grade 6 – 4 showed negative scores. PC2 contrasted Th, Cu, Pb and As with Zr, Rb and Ti but did not discriminate between colour groups. PC3 was dominated by Cu, Pb, As, Cd and Hg and was largely driven by sample 3.I9, which exhibited markedly higher scores than the remaining specimens.

The predominance of Ca and P, together with the stability of the Ca/P ratio, indicates widespread preservation of the bone mineral phase. Al, Si, Fe and Mn are positively correlated with one another and negatively correlated with Ca, suggesting a common source distinct from bone bioapatite. Given the two-mica granite geology of the site, rich in silicates and phyllosilicates, the occurrence of Al and Si, together with Fe and Mn, is consistent with a sedimentary origin (WMS GEODE: Aspiotis et al. 2022). These elements may therefore primarily reflect bone–sediment interaction rather than the original composition of the bone tissue. However, the pXRF data cannot distinguish between diagenetic incorporation into the bioapatite and persistent sediment particles adhering to the bone surface following cleaning.

The heterogeneous distribution of Cu and Pb shows localised enrichment that differs from the general sedimentary signature defined by Al, Si, Fe and Mn. Although pXRF alone cannot establish whether this reflects direct exposure to bronze-working residues, their distribution is compatible with an additional source associated with the metallurgical context. Although calcined bone is generally more resistant to post-depositional alteration owing to its higher bioapatite crystallinity, Cu and Pb may have been incorporated either during cremation through exposure to metallurgical particles or vapours, or after burial through contact with metal-enriched sediments.

Finally, the high proportion of Sn measurements below the LOD suggests that Sn was either absent or present only at very low concentrations in most specimens. This is consistent with its limited mobility under oxidising conditions, where it preferentially forms the stable, low-solubility phase SnO_2, thereby reducing its transfer to porous materials such as bone compared with Cu and Pb (Batzill and Diebold 2005).

Analysis of the metalworking area

As mentioned, the sample context is associated with a metalworking workshop. Its nature can be explored in greater depth through the associated archaeological materials and structures. The recovered materials are consistent with bronze-working activities. However, the context provides no evidence for copper reduction. Copper reduction involves the initial heating of the raw material (most likely pyrite) to form copper matte, following by physical and thermal refining. This process, however, can be difficult to identify, as slag and mineral residues are usually scarce in these structures (Gómez Ramos 1996, p. 128). The furnaces found at A Cividá consist of small, fired-clay hearths that do not fit standard reduction-furnace typologies and would not have been suitable for copper reduction (Craddock 1989). However, these furnaces are clearly compatible with a small-scale smelting site. These structures need

not have been particularly complex, as copper (1,083°C) or bronze (950°C) can be melted at temperatures achievable in relatively simple furnaces. Slag is scarce in this type of furnace, whereas crucibles provide more direct evidence for bronze melting and casting into lost-wax moulds (Armada Pita et al. 2008, p. 475).

The elemental composition of the bone samples provides additional evidence for their association with the metallurgical context, particularly through the elevated Cu/Ca and Pb/Ca values observed. As mentioned, pXRF cannot determine whether these elements were incorporated during metal production, through contact with metallurgical waste, or through post-depositional processes. Nevertheless, considered together, the archaeological and elemental evidence suggest that the bones were exposed to materials associated with metallurgical activities. The deposits show notable material and chronological homogeneity (Taboada Durán 2025), and there are no clear signs of post-depositional alteration or intrusion. The high degree of calcination may also have reduced the susceptibility of the bones to alteration, and they show no signs of subsequent modification. Taken together, these observations support the interpretation that the assemblage was deposited in situ or experienced limited post-depositional disturbance.

With regard to the source of the metallurgical elemental signature, a relationship with copper reduction appears unlikely. Copper was usually reduced near mineral veins, which are absent from the surrounding area (indeed, they are not common in NW Iberia: Montero Ruiz et al. 2014, p. 153), while the furnace structures are not consistent with this type of activity. The presence of Cu and Pb is therefore more plausibly associated with bronze melting and preparation prior to casting. In addition to this structural evidence, the presence of Pb in the bone samples is consistent with exposure to lead-containing bronze alloys, which were widely used from the Early Iron Age onwards (Armada et al. 2023). The presence of crucibles and the associated archaeological contexts further support interpreting the area as a melting/casting-related installation.

In conclusion, archaeological and elemental evidence indicates that the activity area was primarily associated with bronze working, particularly the melting and casting of bronze. The bone assemblage was recovered within this setting, and, considering the absence of clear evidence for substantial post-depositional disturbance and the elevated Cu and Pb values observed, its association with the metallurgical activity is strongly supported. The specific function of the bones remains to be established.

Discussion

The analysis indicates that the A Cividá workshop was used for bronze production, most likely melting and casting. The Cu and Pb enrichment of the bones suggests that they may have been incorporated into the process, consistent with the techniques and materials employed. The key question is whether these faunal remains were deliberately incorporated into metalworking and, if so, what function they may have served.

A multifactorial approach is therefore necessary to determine how and why these bones were involved in metal production. Our initial hypothesis was that the bones were used as bonecoal (Gansum 2004). This technique, already documented in NW Iberia (Nión-Álvarez and Veiga-Rilo 2025), uses bones during forging to create a reinforced cutting edge on iron objects by heating them to release C or P atoms (Markewitz 2023). The presence of calcined bones in a metallurgical workshop allowed this hypothesis to be tested, but the evidence does not support it. The bones show little evidence of association with iron, whereas the archaeological and elemental data instead point to a bronze-working context. Furthermore, workshop data were more clearly associated with a bronze-casting area. Although bronze-working areas may also involve forging activities (Giles 2007), evidence of iron metalworking in this area is rather scarce. Other significant differences include the absence of iron stains on the bone surfaces and the uniform calcination of the A Cividá sample, contrasting with the heterogeneous thermal alteration and abundant iron stains observed at Borneiro (Nión-Álvarez and Veiga-Rilo, 2025, p. 196).

The analyses provide little support for disposal after consumption or substantial post-depositional alteration. If the bones were deliberately associated with the metallurgical activity, they may have served either a thermal or a chemical function. In the former case, the bones would have been used as fuel. The ability of bone to withstand the high temperatures of fires fuelled mainly by wood is well documented in both prehistoric contexts and experimental studies (Théry-Parisot et al. 2005; Mentzer 2009). Although this phenomenon has been reported predominantly in Palaeolithic contexts (Morin 2010; Murphree and Aldeias, 2022), it has also been discussed, albeit less frequently, at more recent archaeological sites (Costa 2016; Mainland et al. 2020). This interpretation is supported by the taphonomic uniformity of the assemblage, with all specimens corresponding to the most advanced stage of thermal alteration (Stiner et al. 1995), and by modifications indicative of prolonged exposure to high temperatures, including extensive surface cracking, volumetric shrinkage, and the extreme fragmentation (Spennemann and Colley 1989; Thompson 2005). However, some aspects do not align with the technical process analysed here. As mentioned earlier, bronze-smelting furnaces do not require the prolonged maintenance of high temperatures associated with fuel generation, making a specific thermal function for the bones less likely.

Regarding the chemical hypothesis, a recent study (Figueiredo et al. 2021) documented the presence of black, bone-derived residue in a palstave axe casting mould found at Guidoiro Areoso, relatively close to A Cividá. The mould preserved black residue produced by the carbonisation of bones in its inner part (Figueiredo et al. 2021, p. 2969). This carbon black substance was interpreted as having been used to smooth the mould, facilitate metal detachment, or provide a moisture barrier. The presence of calcined bones at A Cividá is therefore compatible with the possibility that bone was similarly processed to produce a carbonaceous residue during bronze casting. Although this residue has not been identified at the site, the acidic soils may have hindered its preservation.

Finally, the symbolic hypothesis also warrants consideration, particularly in relation to the widespread ritualisation of bronze metalworking (Herbert 1984). The incorporation of ritualised practices into the production of bronze objects is well documented across several regions of Europe, Africa and Asia. In

the Mediterranean and Levant Late Bronze Age Iron Ages, metalworking workshops were located within temples and played an integral role in organising votive practices (Kassianidou 2005; Susnow and Yahalom-Mack 2023). Lost-wax casting eventually involved ritual practices intended to ensure the successful removal of objects from moulds (Herbert 1984, p. 39–40), potentially involving the black, bone-derived residue discussed above and highlighting the interaction between technical and symbolic practices. Ethnoarchaeological evidence suggests that placing objects in furnaces is a recurring cross-cultural practice (Gosic 2025, p. 177), with melting and moulding interpreted as metaphors for creation or birth (Alberghina 2023, p. 7).

Several cross-cultural examples also document the association between animal remains and bronze production. Sites as geographically distant (although chronologically coherent) as the Baraba forest-steppe near Novosibirsk, Russia, and Midtfeltet in Østfold, Norway, demonstrate how large funerary and votive complexes could incorporate extensive metallurgical activities alongside abundant animal remains (Melheim et al. 2016; Molodin et al. 2020). At Midtfeltet, the bones exhibit post-depositional characteristics strikingly similar to those observed at A Cividá: they lack cut marks, are highly fragmented and display turquoise staining attributed to exposure to bronze (Melheim et al. 2016, p. 60). In this respect, the incorporation of animal remains introduces a “foreign” element into the production process, one that may have been understood through ritualised explanations and symbolic meanings (Schmidt and Mapunda 1997). The inclusion of these remains may therefore distinguish such production contexts from others and prove essential to understanding the biography of the resulting objects. Their production may have acquired social and cultural meaning not solely through the technical processes involved, but also through the symbolic agents mobilised by the practices that led to the inclusion of these bones.

Reconstructing these processes is undoubtedly challenging, and the social and productive systems underpinning such contexts cannot always be recovered. The difficulty of establishing an interpretive framework for the use of animal remains within metalworking activities is a common issue to all the examples discussed here. This uncertainty highlights the importance of publishing such findings to advance the available evidence, as well as pursuing holistic cross-cultural research to develop a more comprehensive understanding of these phenomena.

Conclusion

This study adopted a multifactorial approach to the metalworking context at A Cividá, integrating metallurgical, faunal and statistical analyses to investigate the associated bone assemblage. Together, these lines of evidence indicate that the bones were strongly associated with a bronze-working context. The remains were deposited within the metallurgical area without evidence of prior processing or consumption, suggesting a relationship with metalworking, although their specific role remains uncertain. One possible explanation is that some bones may have been calcined to produce a bone-derived black substance used to facilitate the release of objects from moulds during lost-wax casting. Nevertheless, the scarcity of comparable contexts and the unresolved questions mean that this

hypothesis requires further evidence. Alternative ways of understanding metalworking should also be considered to explore the interaction between technique, symbolism and metallurgy.

More broadly, this assemblage highlights the importance of considering animal remains when reconstructing metalworking contexts, as they have often been overlooked in archaeological interpretations of metallurgical practice. Reconstructing such contexts requires integrating evidence that might otherwise appear anomalous to distinguish incidental deposits from materials potentially involved in technical or symbolic practices and understanding metallurgy as a multifactorial process in which technical, material and symbolic dimensions were closely intertwined. It is crucial to share these findings to bridge the existing gaps in our understanding and facilitate a comprehensive appreciation of bronze metalworking in the past.

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Author Contribution

- Author’s contributions:SNA: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, supervision, visualization, writing (original draft), writing (review and editing).CVR: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing (original draft), writing (review and editing)HBG: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing (original draft), writing (review and editing)ETD: data curation, funding acquisition, investigation, writing (review and editing).All authors read and approved the current version of the manuscript

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Figures

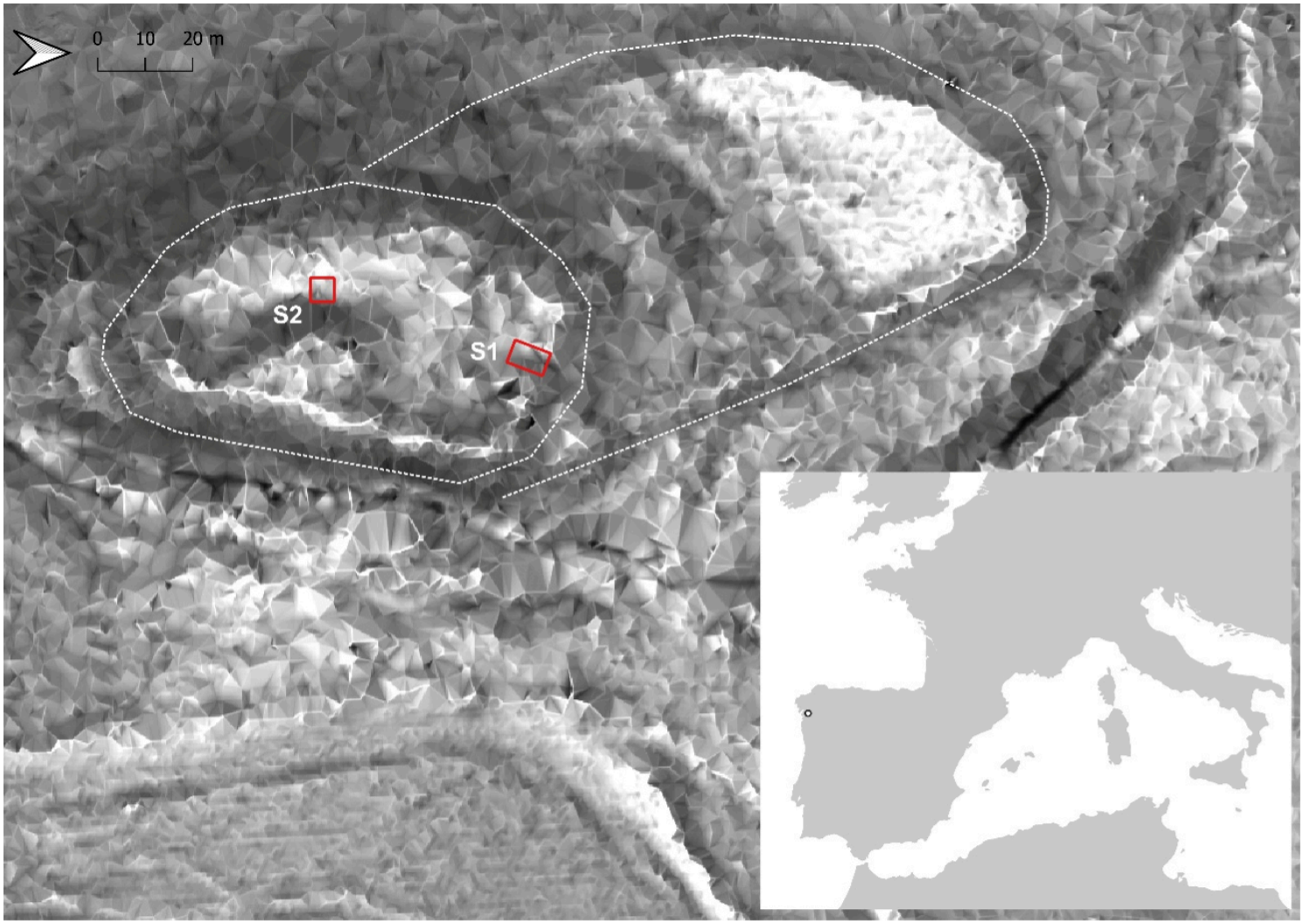


Figure 1

Location and site, including archaeological surveys[1]

[1] All figures were created by the authors.



Figure 2

Aerial view of the site

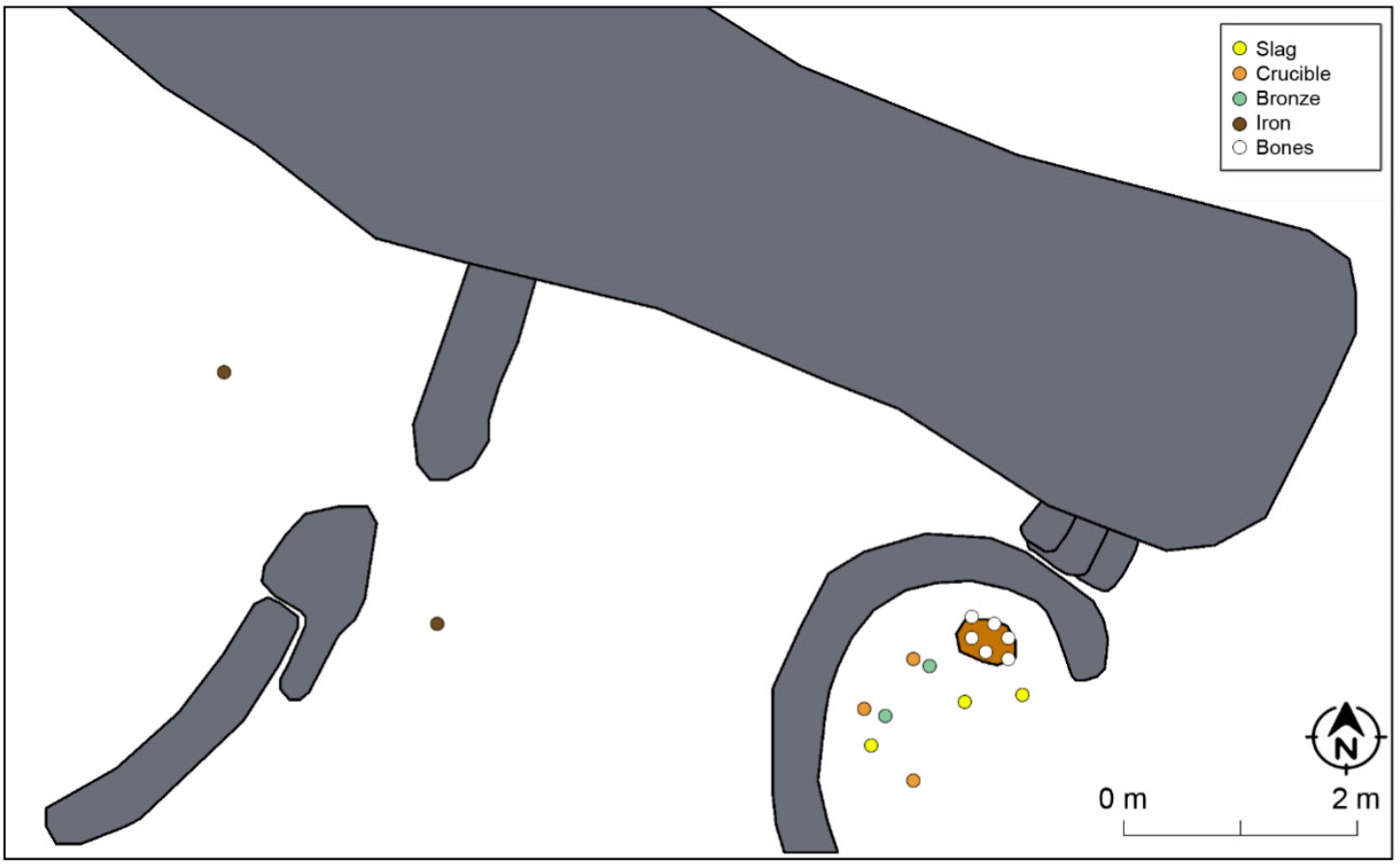


Figure 3

Finds associated with metal production



Figure 4

Metalworking workshop (left) and location of the bone deposit (right)



Figure 5

Crucibles with scorifications

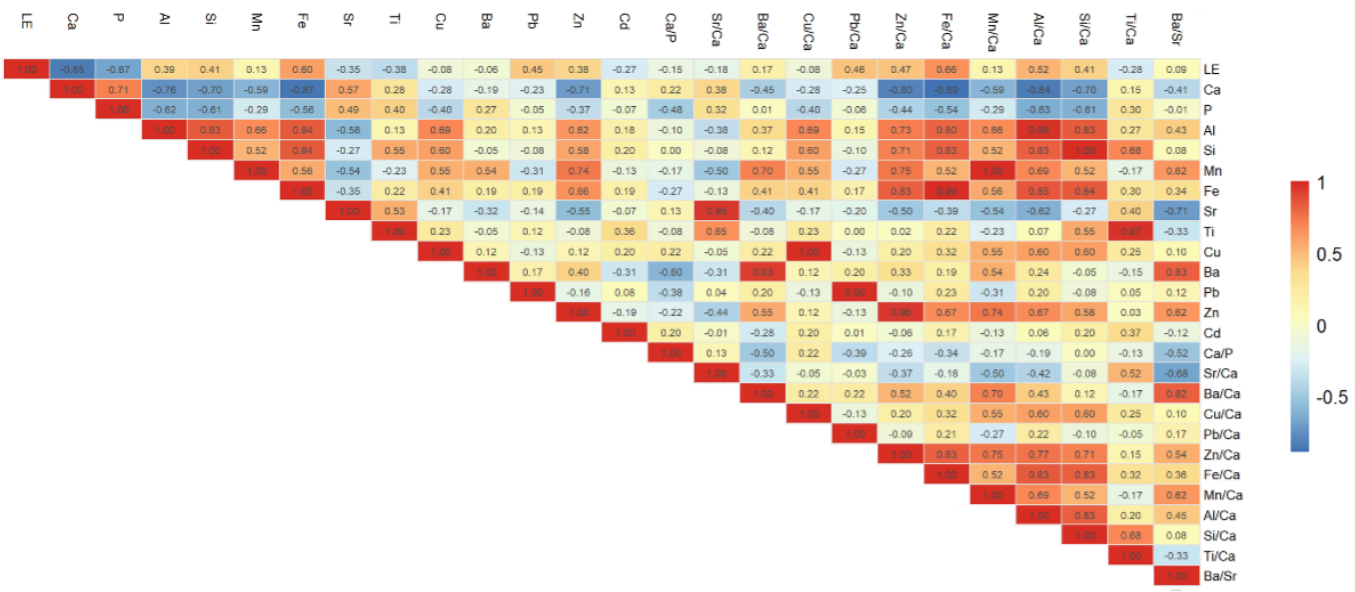


Figure 6

Spearman correlations Heatmap. Upper triangular heatmap of Spearman's rank correlation coefficients (ρ) among elemental concentrations and geochemical ratios measured by pXRF. Positive correlations are shown in warm colours and negative correlations in cool colours, with colour intensity proportional to the correlation strength.

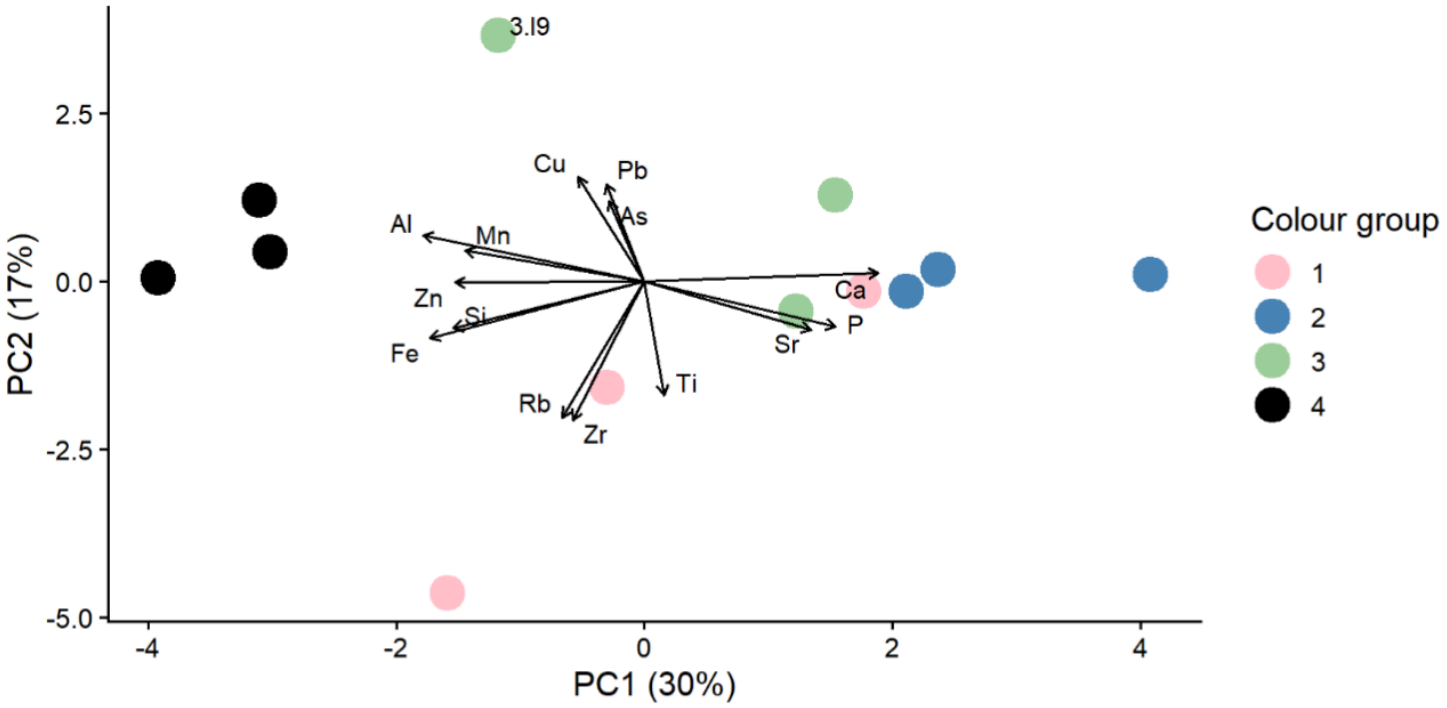


Figure 7

Biplot PC1-PC2. PCA biplot of PC1 and PC2 based on pXRF elemental concentrations. Points represent individual bone samples coloured by macroscopic surface colour groups, whereas arrows represent the loading vectors of the selected elements. The first two principal components explain 46.6% of the total variance (PC1 = 30%; PC2 = 17%). Sample 3.I9 is labelled because of its distinct position within the multivariate space.

Supplementary Files

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