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The technological dichotomy under debate: The *chaînes opératoires* of copper metallurgy in the third millennium BC in the Upper Guadalquivir (southern Spain)

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ABSTRACT

The interpretation of metallurgy in the so-called *Chalcolithic* period (late 4th-3rd millennium BC) in the Iberian Peninsula has historically been dominated by a paradigm that attributed to its southern region a secondary, dependent role and an inability that defined it as a simple system with a low degree of specialisation, low production capacity and reduced demand for metals. At the technological level, this model was defined by metallurgical knowledge whose domestic application slowed down its sophistication of its methods and resulted in typological monotony and the continuity, for centuries, of the *chaînes opératoires* of manufacturing. This led to the postulation of a profound dichotomy between the south-eastern and south-western regions. This article presents a direct refutation of this model through the archaeometallurgical analysis of a corpus of 30 copper products dating from the third millennium BC, recovered from three key sites in the Upper Guadalquivir: Marroquíes Bajos, Las Eras del Alcázar and Castro del Río. By applying an analytical protocol that integrates metallographic microscopy, electron probe microanalysis (EPMA) and *Vickers* microhardness tests, the *operational chain* implemented is reconstructed. The results reveal remarkable technological consistency and a total absence of simple manufacturing sequences (smelting and forging). On the contrary, the systematic mastery of complex production processes is evident, with a combination of forging and annealing cycles, representing 100% of the sample. This suggests a sophisticated *technological tradition* shared throughout the southern peninsula, which forces us to reconsider models of craft specialisation, knowledge transmission and social interaction networks in this period.

1. Introduction: The deconstruction of a paradigm

1.1. The traditional model: A narrative of emulation and regional dichotomy

For decades, academic discourse on the emergence and development of metallurgy in the Iberian Peninsula has been structured around research and narratives marked by regional asymmetry and dissimilarity. The westernmost region of Europe was interpreted on the basis of a model that attributed to it a secondary and dependent role in this process, with limited technological and social development, characterising metallurgy as a domestic production activity, defined by the absence of spatial division of labour, the absence of sophisticated production techniques and technology and, in general, by its almost invisible impact. In contrast, metallurgy in the East (including Europe, but excluding Iberia) was defined by opposition (Amzallag, 2009; Bourgarit, 2007; Cámara and Molina, 2006, 2016; Champiom et al., 1984; Chapman, 1990; Childe, 1954; Cunliffe, 1994; Delibes and Fernández, 1993; Fernández-Miranda, 1987; Gills, 1995; Gills and Frank, 1993; Gilman, 1996; Molina et al., 2016; Montero, 1993; Montero et al., 2021; Ottaway, 2001; Roberts, 2011; Roberts et al., 2009; Rothenberg, 1990; Rovira, 2002; Tylecote, 1987).

However, and despite the fact that in the south-west of the peninsula, where numerous important copper mineralisations were known, such as the Iberian Pyrite Belt (Sáez et al., 1996), it seemed impossible to document significant records of mining and metallurgical exploitation in its earliest and most ancient phases of development (Hunt, 2003; Hunt Ortiz and Hurtado, 1999; Lazarich, 1987; Montero, 1994, 1999; Pérez Macías, 1996 a; 1996b).

Though, in other areas of the south of the Iberian Peninsula (central

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and eastern), traditional historiography repeatedly presented the *original metallurgical centres*, where metallurgical research has been systematically developed, as one of the main avenues for understanding their societies (Lull et al., 2010). Their interpretation was that of a linear and evolutionary model that conceptualised domestic metallurgy as economically irrelevant, with discreet development and no control over production, justified by the lack of structured political structures and the geographical dispersion and scattered distribution of copper mineralisation. The impossibility of controlling and monopolising these deposits seemed to define the main model of interpretation of metallurgy in the southeast and, through a simple untested mechanism of emulation, that of the entire Prehistory of the Iberian Peninsula (Montero and Murillo Barroso, 2014; Montero et al., 2021; Murillo Barroso and Montero, 2012; Rovira, 2002, 2016; Rovira, Montero, 2013).[1]

This is particularly significant because the interpretation of the technological analysis carried out for the early stages of metallurgy in the Iberian Peninsula was based on a partial study of the south-east, but if we look at the archaeological sites documented with evidence of metallurgy for the third millennium BC in the south-east of the Iberian Peninsula, we realise how limited their archaeometallurgical analyses are, especially when compared to those of later periods (*Argaric*) (Lull et al., 2010). And although the study of the technical chains of metal product manufacturing had not been addressed systematically, this did not prevent us from arguing that metallographic studies outlined clear features that supported the idea of a slow development in technological knowledge and mastery (Montero, 2010; Montero and Murillo Barroso, 2010; Montero et al., 2021; Murillo Barroso and Montero, 2012; Rovira and Gómez, 2003).

Within this interpretative framework, following the solid proposal for a model shift (see *below*), complex manufacturing processes, in particular the controlled use of heat treatments, came to be considered distinctive features of the southwest, but it was still assumed that metallurgy in other regions, especially in the southeast and the Upper Guadalquivir, was dominated by simple manufacturing sequences (Montero and Murillo Barroso, 2014; Rovira, 2002, 2016; Rovira and Gómez, 2003).

1.2. A paradigm shift from the southwest

The conceptual and methodological turning point that challenged this paradigm originated in the Southwest Peninsula's. Extensive research programmes, focused on the main mining district in Western Europe, the Iberian Pyrite Belt, made it possible to identify metallurgical production contexts of unprecedented age and complexity (Bayona, 2008, 2015; Nocete, 2001, 2004, 2006; etc.). The sites of Cabezo Juré (Alosno, Huelva) and Valencina de la Concepción (Seville) emerged as key references, documenting intensive and specialised production processes that explicitly refuted the interpretation of a secondary, dependent and technologically limited metallurgy (Bayona et al., 2003, 2010; Bourgarit, 2007; Nocete, 2001, 2004, 2006, Nocete et al., 2005a, 2005b, 2005c, 2008, 2011, 2014; Sáez et al., 2021). This traditional paradigm implied enormous simplicity and very low productive capacity and interaction with the consolidation of emerging models of social complexity (Montero and Murillo Barroso, 2016; Obón et al., 2020[2]; Rovira, 2002, 2016; Rovira and Montero, 2018; Valério et al., 2020, 2023; etc.). This interpretative model offered a technological explanation based on a partial analysis of metallurgy, where contexts of production, were practically absent from the arguments of its proposals. However, it is acknowledged that this situation changed with the so-called *Orientalising period* (Hunt Ortiz and Hurtado, 1999), when it was accepted without reservation that silver and iron metallurgy in the 1st millennium BC became an important economic activity throughout the Peninsula (Arana et al., 1993): *Ex Oriente Lux*….

This paradigm shift from the southwest was not based on isolated findings, but rather on the implementation of a rigorous and systematic regional research programme, which was fundamental in the field of archaeometric studies focused on the manufacture of copper products (Bayona, 2008, 2015; 2018). This programme focused on the theoretical and analytical evaluation of technical and social processes using a systematic protocol that included the study of elemental chemical composition by electron probe microanalysis (EPMA), microstructural analysis and the evaluation of mechanical properties through microhardness testing. This approach, applied to samples from systematic excavations and well-defined archaeological contexts in Cabezo Juré and Valencina, among others, not only significantly increased and created the largest corpus of analytical data for the third millennium BC, but also established a solid empirical basis from which to re-evaluate traditional models of interpretation. The analysis of this corpus confirmed the significance and validity of an alternative technological model, demonstrating that the application of heat treatments (annealing) was not anecdotal, but a recurring and integral part of the manufacturing sequences. This refuted, once and for all, the traditional interpretation that gave predominant weight to simple production techniques (C + H),[3] demonstrating a clear intention to control production conditions and techniques in order to obtain products with specific and more efficient qualities (Bayona, 2008, 2015). This was the real starting point that dismantled the notion of "primitive" metallurgy, but raised the need to verify whether this complexity was a phenomenon exclusive to the Southwest, which had become an exemplary framework for reflection. On this basis, the discussion on the chronological, technological and social development and the concepts and perception of prehistoric copper metallurgy were redefined and subjected to a profound process of debate and reflection (Bayona, 2008, 2015; Bourgarit, 2007; Cámara and Molina, 2006, 2016; Comendador Rey, 1999; Nocete, 2001, 2004; Nocete et al., 2011, 2014; Sáez et al., 2021; etc.).

1.3. Research hypothesis

This article addresses the central question, seeking to determine whether the technological gap proposed by traditional models is empirically verifiable and valid. We address this problem through the concept of *technological tradition,* defined here not simply as a set of techniques, but as a structured system of knowledge, practices and operational sequences, shared and transmitted within and between communities, which shapes the approach to material transformation (Costin, 1991; Dolfini, Crellin, 2016; Lemonnier and Speth, 1992).

Our basic hypothesis is that, contrary to the established archetype, the technological traditions fundamental to the manufacture of copper products were significantly homogeneous throughout the southern Iberian Peninsula during the third millennium BC. We postulate that the artisans of the Upper Guadalquivir, far from practising exclusively this so-called domestic and simple metallurgy, operated within the same complex technological framework documented in the Southwest. This study therefore aims to provide (more) reliable evidence to refute the division between "simple" and "specialised" metallurgy, clearing the

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[1] However, recent studies have highlighted the weak empirical support for the proposal of a domestic and non-specialised metallurgy in the southeast and the inability of this model to interpret the records documenting the existence of a workshop specialising in copper production in Los Millares (Cámara, Molina, 2006, 2016).

[2] This publication presents inconsistencies in its arguments, since epistemological refutation is not addressed, at least in terms of the interpretation of metallurgical activity at sites such as Cabezo Juré. Furthermore, in order to refute an interpretative model, we understand that this cannot be done exclusively through *experimental archaeology*.

[3] To follow the terminology used in other publications, C: casting; H: hammering; A: annealing and FH: final hammering. In this case, hammering and forging are used as synonyms, the same as casting and smelting.

way for diverse and nuanced models of craftsmanship, knowledge transmission and social interaction in absolute chronologies of the 4th-3rd millennia BC.

This requires research strategies in alternative temporal and/or spatial frameworks that provide the necessary historical perspective required to explain these processes. A synchronous reading is needed from which to evaluate copper metallurgy in diachrony (Fig. 1).

1.4. Challenging historiography: A critical approach to the "Centre of Origin"

The decision to focus this study on the sites of the Upper Guadalquivir is not accidental, but responds to a fundamental methodological need to confront the roots of the traditional paradigm. Traditionally, historiography has considered and continues to consider the south-east of the Iberian Peninsula as the "original centre of metallurgy in the current territory of Spain" (Martínez, 1989). This perspective, often framed within diffusionist models, understood that the need for mining and metallurgical resources drove the movement of communities from the Aegean, establishing colonies that would introduce metallurgy to Europe, finally reaching the south-east of the peninsula. In this account, sites such as Los Millares (Santa Fe de Mondújar, Almería) became the archetypes of early metallurgical cultures, from where this "innovation" would have spread to other areas (Bayona, 2008, 2015).

This conception had profound consequences for the direction and focus of the research carried out. For a long time, debates on inter-social relations and technology transfer in the third millennium BC were articulated almost exclusively on the basis of records from the southeast, under models such as *Peer Polity Interaction* (Nocete, 2001). It was often uncritically assumed that technological differences between the "East" (the southeast) and the "West" (the southwest) were equivalent parameters of analysis, without taking into account the absolute chronological differences that new data were revealing (Costa, 2010; Nocete et al., 2011). Paradoxically, while metallurgical activity in the southwest went from being discredited for its supposed simplicity to breaking the paradigm (see *above)*, Eastern metallurgy (including that of the Iberian southeast) was defined and characterised without rigorous and systematic empirical comparison of its chronology or production technology and with a total absence of studies of its *operational chains* (Amzallag, 2009[4]; Montero, 1994). However, although misguided, there is research that places the south-west of the peninsula at the centre of the most homogeneous traditional view of metallurgical activity (La Duc et al., 2022).

Therefore, in order to contrast and subsequently refute this model, it was not enough to demonstrate the complexity of the southwest (Bayona, 2008, 2015; Bayona et al., 2003, 2010; Nocete, 2001, 2004, 2006; Nocete et al., 2005a, 2005b, 2005c, 2008, 2011, 2014; Sáez et al., 2021; etc.), but it was also methodologically imperative to apply the same analytical and experimental approach in the spatial areas of the supposed "centre of origin". It was necessary to construct the model from within, assessing whether the material basis of its metallurgy really supported the claims of technological simplicity in contrast to that of other areas. This work, based on the aforementioned research programmes, responds directly to that need. By selecting sites from the central and eastern core of Andalusia (Upper Guadalquivir), we have articulated an explanation that covers almost the entire southern peninsula, allowing us to characterise and contrast the metallurgical activity in these territories in a rigorously scientific manner. This approach allows us to move beyond the traditional discourse and evaluate, through direct evidence from copper products, the true nature of their *technological tradition.*

Copper and its alloys bear the history of a resource whose production, circulation and hoarding were involved, in one way or another, in the establishment, structuring and consolidation of class relations in and between the societies of the Iberian Peninsula in the past.

2. Archaeological contexts, materials and analytical methodology

2.1. Archaeological sites: Production contexts in the Upper Guadalquivir

The selection of the empirical universes and archaeological contexts relevant to this study has been based on their relevance for characterising metallurgical activity in the Upper Guadalquivir in the third millennium BC. Marroquíes Bajos (Jaén), Las Eras del Alcázar (Úbeda, Jaén) and the sites around Castro del Río (Córdoba) represent different but contemporary models of settlement and social organisation, making them ideal laboratories for assessing the variability and consistency of technological traditions on a regional scale (Fig. 2). In addition to these premises, it should be noted that there are few other cases that could provide contextualised, dated and complementary archaeological records for the study of metallurgical activity in this area (Lizcano et al., 2004).

With regard to the rescaling of the spatial scale to cases in Central and Eastern Andalusia (Upper Guadalquivir) from the 3rd millennium BC in this study, it should be noted that, of the selected archaeological sites and finds, there were no previous analyses, except those carried out by ourselves for Las Eras del Alcázar (Bayona, 2009).

2.1.1. Marroquíes Bajos (Jaén): A mega-site of organised production

The Marroquíes Bajos site, located in the current urban area of Jaén, is one of the most unique and complex prehistoric settlements in the south of the Iberian Peninsula (Fig. 3). Its definition as a "macro-village" is based on its vast size and, above all, on its sophisticated spatial organisation, articulated by a system of up to five concentric moats that delimit different areas of habitat and production, with a maximum walled area of 340.000 m^2 (Hornos et al., 2000; Zafra et al., 2010; Zafra et al., 1999).[5] This monumental engineering, according to its authors, feat not only demonstrates a large population, but also a complex social organisation capable of mobilising and coordinating a huge workforce, making it one of the most representative examples of the large prehistoric settlements in the countryside of the province of Jaén (Díaz del Río, 2004) (Fig. 4). This site has recently been included in a group of seven *mega-sites* from the *Copper Age* in the Iberian Peninsula, as a particular expression of large settlements with low population density (García Sanjuán and Sánchez Díaz, 2025).

The settlement is located in a strategic position, in the foothills of the Sierras Subbéticas (Fig. 5), controlling the transition to the fertile lands of the Guadalquivir countryside. Its geological substrate of Miocene marl, which is easy to excavate, was extensively used for the construction of underground and semi-underground structures, including the moats themselves (Espantaleón, 1960; Lizcano et al., 2001a, 2001b, 2001c; Sánchez et al., 2005).

The chronology of metallurgical activity in this study falls within the phase of maximum occupation of the settlement, between 2.580 and 1.860 cal BC (Cámara et al., 2012a, 2012b; Aranda et al., 2016). With regard to the age of the metal products from the depositional contexts of Marroquíes Bajos selected for this study, radiocarbon dates related to the phases, structures and/or stratigraphic units from which they originate place them in the interval 2.550–1.950 cal BC (Cámara et al., 2012a, 2012b).

The evidence of metallurgical production is not anecdotal, as copper-based products (punches, Palmela points, needles, metal wires, metal

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[4] This work has been strongly criticised in Thornton et al., 2010.

[5] However, the proposal of concentric moats is not accepted by all researchers, as the numerous but partial and isolated interventions at this archaeological site prevent the solid construction of a comprehensive explanatory model of the site.

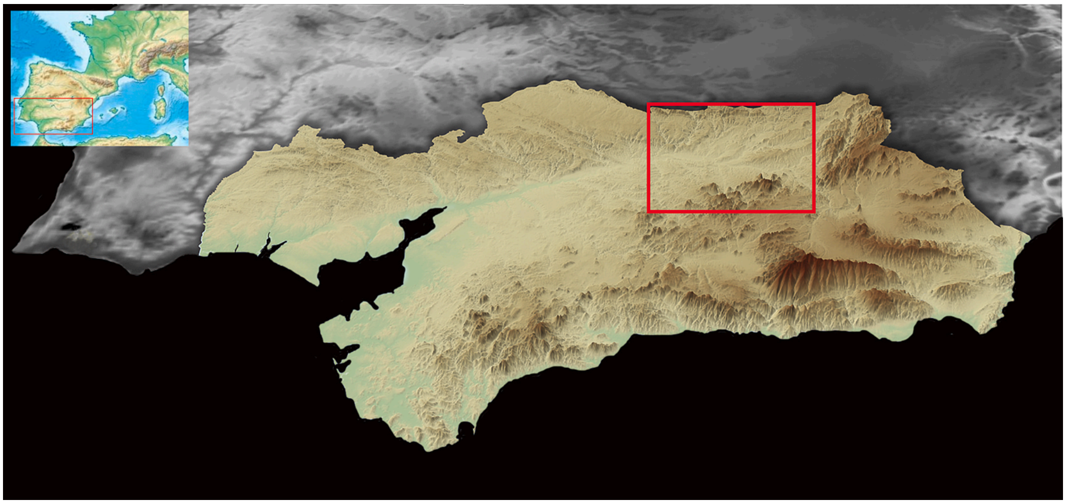

Fig. 1. Spatial delimitation of the territorial scope of the research.

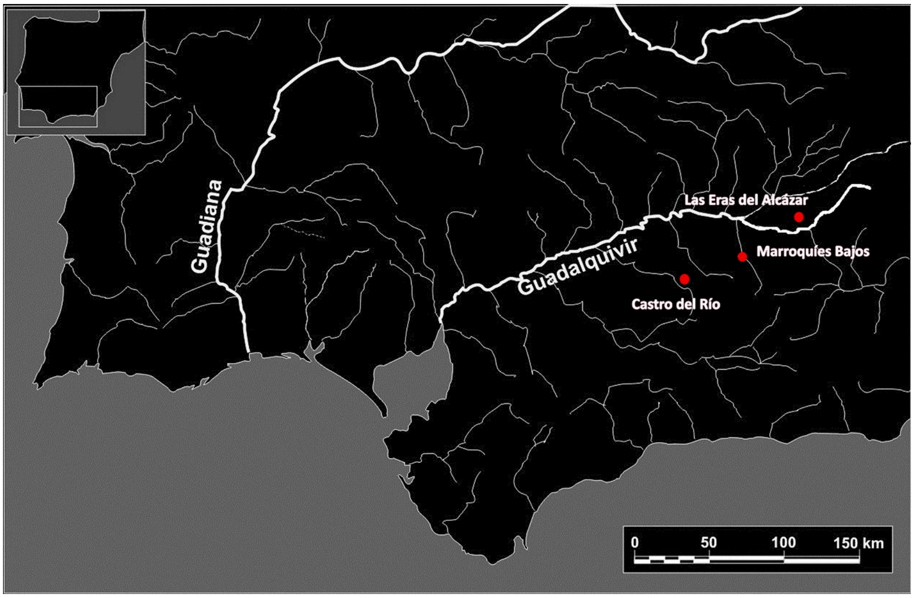

Fig. 2. Location of the archaeological sites and contexts of this study: Marroquíes Bajos, Las Eras del Alcázar, Castro del Río. Coastline in the Third Millennium BC. Adapted from Bayona, 2018.

fragments, etc.) have been documented both in domestic units and in sectors that have been interpreted as specialised workshops, such as Structure 52 or C.E. 823, where the presence of crucibles, slag, mineral remains and underground structures defined as furnaces has been recorded (Aranda et al., 2016; Cámara et al., 2012b; Nocete et al., 2011; Pérez and Cámara, 1999; Pérez and Lizcano, 2003; Pérez and Sánchez, 1999; Zafra, 2011; Various authors, 2010). The analysis and interpretation of the archaeological contexts of Marroquíes Bajos suggests specialised full-time production (*workshop at household level)* defined by the use of specialised technology focused on the manufacture of copper elements in small production units where the origin of the minerals is located at least 20–30 km away (Nocete et al., 2011).

The definition of this model of production organisation suggests a complex economic system,[6] where metallurgy was integrated into different levels of social life, making Marroquíes Bajos a crucial context for discussing models of specialisation.

2.1.2. Las Eras del Alcázar (Úbeda, Jaén): A regional centre with a long diachronic sequence

The Las Eras del Alcázar site is located on a flat spur that visually dominates the Guadalquivir valley, a privileged geostrategic position over the most fertile lands that allowed the development of agricultural economies, as well as favouring direct control of the territory and optimal natural defence conditions (Fig. 6). Its main scientific value lies in its extraordinary and continuous stratigraphic sequence, which spans more than two millennia, from the 4th to the 2nd millennium BC (3533 ± 103 and 1831 ± 48 cal BC), making it one of the most important sites for the study of Recent Prehistory in Andalusia (Lizcano et al., 2009; Nocete et al., 2010) (Fig. 7).

During the period in question, the third millennium BC, Las Eras del Alcázar became a large settlement covering more than 6 ha, which, together with its uninterrupted development, made it the largest sequence of recent prehistory in the Upper Guadalquivir and a regional centre of the first order (Carrión et al., 2012; Fuentes et al., 2007; Lizcano et al., 2009; Lizcano et al., 2010; Nocete, 2001).

In the context of Las Eras del Alcázar, significant metallurgical

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[6] See Cveček, 2023 for a conceptualisation of the model.

Fig. 3. Archaeological structures related to metallurgical production in Marroquíes Bajos.
Source: Nocete et al., 2011

activity has been identified, documented by the presence of copper minerals and slag, production tools such as crucibles and tongs for handling these minerals, and a wide range of metal products (punches, knives, needles, etc.). However, the preliminary absence of facilities and means of intensive production (reduction furnaces, nozzles, etc.) indicated that this activity was mainly carried out in areas of craft production aimed at supplying the community (Lizcano et al., 2009; Lizcano et al., 2010). Therefore, in terms of scale, it represented contexts of part-time domestic production without technical or spatial division of labour (*Complete Household Production)*. However, this domestic production model would be transformed in the final phases of occupation (c. 2200 BCE) into a model of spatial division (*Workshop at household level)* (Nocete et al., 2011). The metal products analysed in this study come from archaeological contexts that date them to between 2.715 and 1.800 cal BC (Nocete et al., 2010, 2011) (Fig. 8).

This variety in the scale and spatial organisation of production, compared to other socio-technological models, such as that of the southwest, makes Las Eras del Alcázar a fundamental case study for determining whether the documented differences also imply differences in the underlying *technological tradition*.

Fig. 4. Detail of the archaeological excavation of a sector of the extensive prehistoric urban occupation of Marroquíes Bajos.
Source: Various Authors, 2010

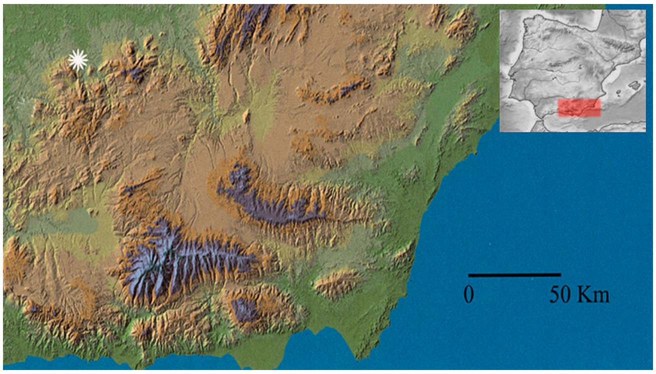

Fig. 5. Location and spatial scope of Marroquíes Bajos on the Iberian Peninsula. Adapted from Cámara et al., 2012b.

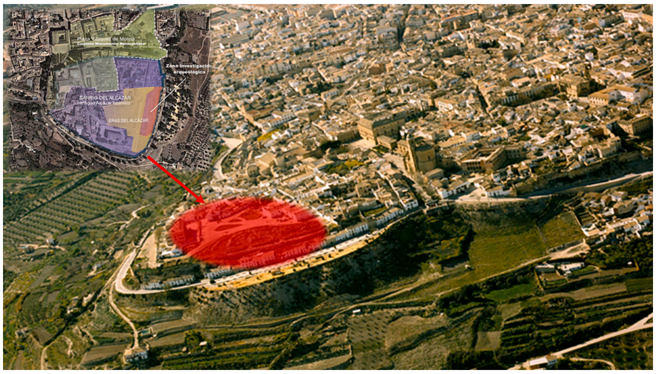

Fig. 6. Location of the prehistoric archaeological contexts of Las Eras del Alcázar in the city of Úbeda (Jaén).
Adapted from Lizcano and Gómez, 2015.

2.1.3. *Castro del Río (Córdoba): Metallurgy in a dense landscape of agricultural settlements*

The context of Castro del Río differs from the previous two. It is not a single site, but a densely populated territory in the fertile Cordoba countryside where, during the third millennium BC, a multitude of agricultural settlements flourished (Fig. 9). Research in this area has

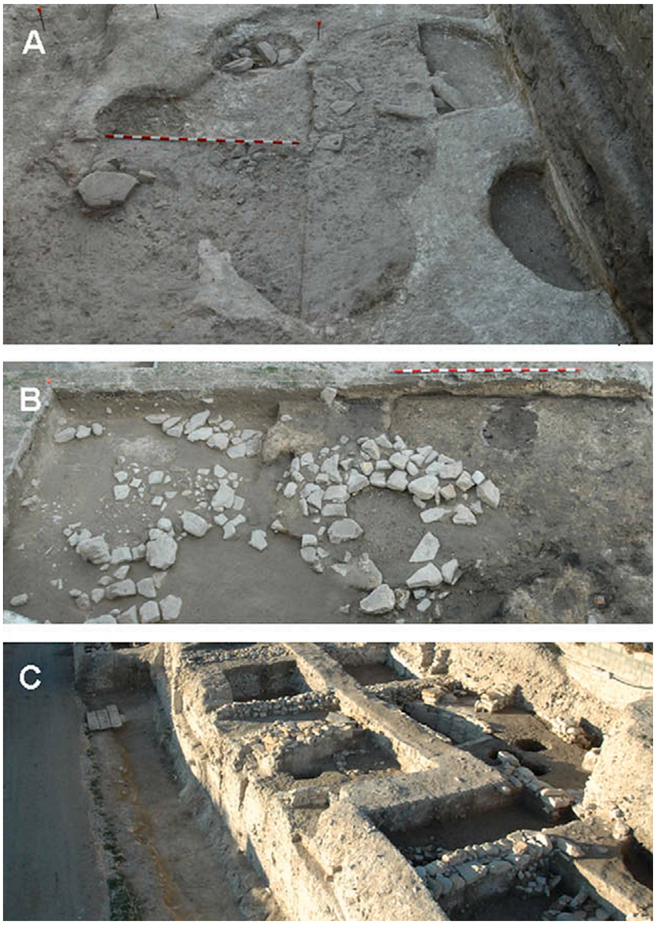

Fig. 7. Construction process at Las Eras del Alcázar: (A) c. 3.000 BCE (B) c. 2.200 BCE (C) c. 2.000 BCE.
Source: Nocete et al., 2010

Fig. 8. Tomb T-13 at Las Eras del Alcázar with male burial. In the foreground, dagger UB-13003-T13 (analysed in this study) and silver artefacts.
Source: Nocete et al., 2010

revealed a high density of sites known as *Chalcolithic,* such as Guta, La Polonia, Viña Boronato and La Tiñosa, which formed a network of interconnected communities (Carrilero and Martínez, 1985) that were occupied from the middle of the 4th millennium BC (Martínez et al., 2014). The *Cordoba countryside*, especially its lower countryside, is considered the cornerstone of a geographical area that is essential for the interpretation, understanding and analysis of the socio-economic processes that took place in prehistory, both locally and regionally (Carrilero, 1990, 1993).

The chronology of these settlements is established mainly by typological correlations (e.g., presence of bell-shaped pottery) and stratigraphic correlations with nearby sites that are better dated, placing them contemporaneous with Marroquíes Bajos and Las Eras del Alcázar, thus giving them validity and representativeness within the framework of this work. The material analysed in this study comes from several of these sites (Viña Boronato, La Tiñosa and Cerro Morcilla), thus representing the metallurgical landscape of this micro-region, based on the availability and characteristics of the research.

The archaeometallurgical evidence in this territory is remarkable for its abundance, present in almost all archaeological contexts in the area (Guta, Viña Boronato, La Tiñosa, Morales, Huesa la Baja, etc.) (Carrilero et al., 1982). Sites such as Guta have been described as “regional metallurgical centres” due to the enormous quantity of copper products recovered (more than 20 kg), which include not only finished products but also fragments and broken remains, which could suggest significant remelting and recycling activity, although the presence of slag and crucibles also confirms, according to its authors, local production (Carrilero, 1990, 1993; Carrilero and Martínez, 1985). More than a hundred punches, around twenty javelin or Palmela tips, tongue daggers, chisels, etc. have been documented. Alongside these, there are constant references to raw materials, means of production and remains of the production process such as minerals, slag and crucibles, in sites such as Guta and Morales.

Thus, despite the lack of contextual analyses of metallurgical production, a significant metallurgy has been outlined, with examples in which the scale of activity reached very high levels, as indicated by F. Nocete et al. (2010): *by c. 2100 to 2000 BCE, in the Upper Guadalquivir Basin there emerged a specialised copper workshop industry in peripheral mining and smelting settlements, such as Peñalosa, in the mining district of Linares-La Carolina, and the circulation of copper ores and the rise of copper workshop areas in regional centres, such as Guta, Tiesas, Aragonesas, Cástulo and Marroquíes.*

This context of dispersed but intense production in a rich agricultural landscape offers a crucial counterpoint to more centralised production models, allowing us to investigate the penetration of technological knowledge into the socio-economic fabric of the agricultural communities of the period covered by this study.

2.1.4. *Metallurgical background*

Although research into prehistoric metallurgical activity has been one of the main avenues for understanding societies in the south-east of the Iberian Peninsula, particularly during the *Argaric period*, the main aspects of this analysis have focused on the origin and characterisation of raw materials, the evolution of the chemical composition of metals, working processes and the role of metallurgy in socio-economic dynamics (Escanilla et al., 2025; Castro et al., 1999).

Although this spatial area has been constantly present in debates on the origins and social impact of metallurgy, and although numerous research projects have been and are currently being carried out in areas of considerable metallurgical importance and with settlements that are, in some cases, very significant (Los Millares) (Molina and Arribas, 1993; Molina and Cámara, 2005), contextual and detailed studies have been limited, especially those involving the analysis of manufacturing techniques and microscopic metallography, which is not a widely developed methodological procedure in this type of research, except for specific contributions in particular cases and sites. The number of metallographic analyses carried out for the entire south-east, both for the *Chalcolithic* and *Argaric* periods, does not exceed thirty (Rovira and Gómez, 2003), although in the last decade there has been a small increase, which is by no means systematic or representative.

This can be seen from the fact that, from the so-called *Chalcolithic* period, which a priori would best fit the chronological spectrum of this

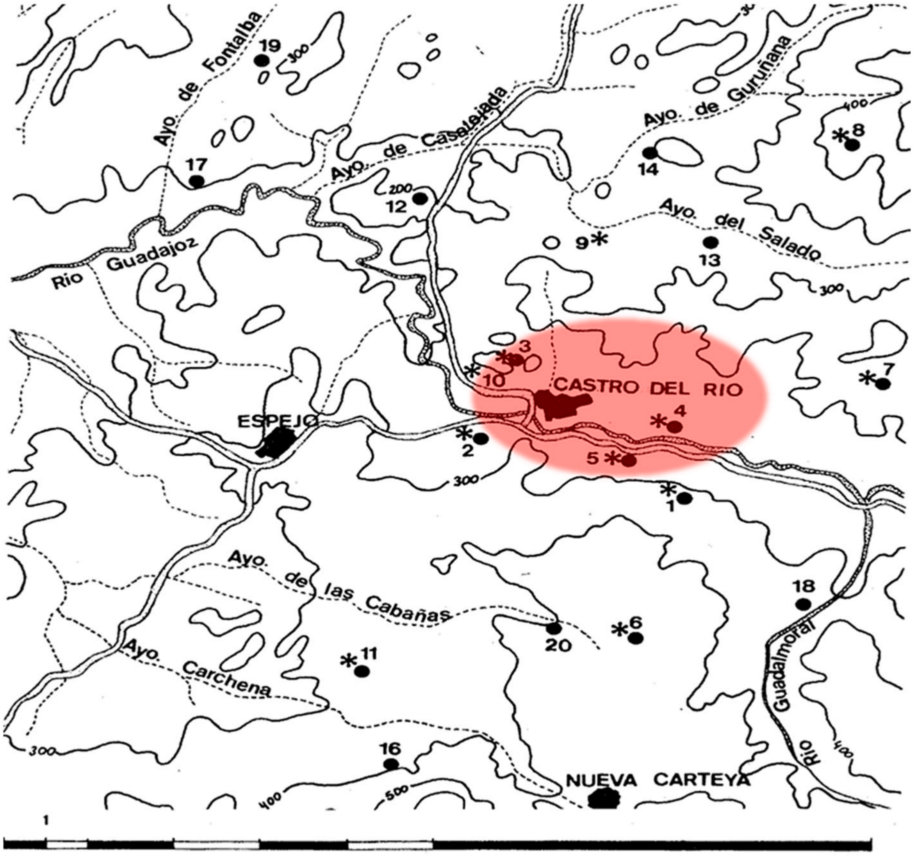

Fig. 9. Prehistoric settlement of the Córdoba countryside in the vicinity of Castro del Río: 1, Guta; 2, San Joaquín; 3, La Polonia; 4, Venegas III; 5, Viña Boronato; 6, Morales; 7, La Tiñosa; 8, Loma Cuadradillo; 9, Colegio; 10, El Molinillo; 11, Casa Vega; 12, Huesa la Baja; 13, Los Carambolos; 14, La Gamonosa; 15, Praena; 16, Los Almiares; 17, Ategua; 18, Gutilla; 19, El Jardón; 20, La Cebadera (* Middle and/or Late Neolithic; • Copper Age).
Adapted from Carrilero and Martínez (1985).

work, a small number of analyses of metal products have been collected from sites such as El Malagón (Cúllar-Baza, Granada), Cerro de la Virgen (Orce, Granada), Los Millares (Santa Fe de Mondújar, Almería),[7] Cerro Virtud-Herrerías and Almizaraque (Cuevas de Almanzora, Almería),[8] El Gárcel (Antas, Almería), Las Angosturas (Gor, Granada) and Las Peñuelas and Los Eriales (Laborcillas, Granada). To this group should be added the analyses carried out on products from Los Millares and El Malagón by a research team attached to the British Museum, the University of Granada and the Johannes Gutenberg-Universität Mainz (Hook et al., 1991; Keesmann et al., 1991–1992).[9] From the same area, but from later periods, known as *the Argaric world,* only a few products have been analysed (Rovira and Gómez, 2003). Sites such as Hoya de la Matanza (Senes, Almería), Cerro de Enmedio (Pechina, Almería), Las Angosturas and Llano de la Gabiarra 86 (Gor, Granada), Peñón de La Reina (Alboloduy, Almería) and the El Argar site itself (Antas, Almería) are referred to. In most cases, these are isolated analyses of between one and three metal products, and when this number is exceeded, the analyses usually correspond to production residues rather than copper products or remnants of copper products.

As regards the spatial framework of this work, practically no analyses or metallographic studies have been carried out on products linked to the period covering the third millennium BC, with the cases analysed (10 in total) belonging to what their authors refer to as *the Early Bronze Age* and *Middle Bronze Age*. These would be the sites of El Encinarejo (Posadas, Córdoba), LLanete de los Moros (Montoro, Córdoba) and decontextualised materials from Nueva Carteya, Montalbán, Pedro Abad and Santaella (Córdoba) and Méngíbar (Jaén) (Rovira and Gómez, 2003).

However, further research and expansion of case studies reveal that few works have been published for the province of Córdoba, with the exception of metallographic studies associated with the analysis of the provenance of materials from the Islamic period in *Madinat al-Zahra* (Gener et al., 2014). Other related works include those more oriented towards surface prospecting with an archaeometallurgical approach than towards the study and characterisation of production techniques (Contreras et al., 2005; Fernández et al., 1992, 1993, 1995; Rodríguez et al., 1991). Fortunately, there are recent publications that address the various copper production strategies in what they refer to as areas outside the traditionally studied zones (southeast and southwest), suggesting greater technological diversity for *the Chalcolithic period.* This would be the case of the study of the Cueva del Cañaveralejo site (Córdoba), whose metallurgical activity dates back to the third quarter of the third millennium BC. Although no metallographic analyses have been carried out, studies of slag, minerals and Cu *prills* using lead isotope and composition analysis are an excellent contribution (La Duc et al.,

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[7] The archaeometallurgical research at Los Millares, however, must be recognised for its remarkable exceptionality within the general framework of its spatial scope.

[8] Most of the analyses of this site (10) correspond to smelting remains or nodules, and not to products or product remains.

[9] In a recent study on contexts from the 3rd millennium BCE at the Las Pilas site (Mojácar, Almería) (Murillo et al., 2017), the authors claim to have documented the entire metallurgical production process. However, despite numerous archaeometallurgical characterisation analyses, the metal products, which were very scarce, were only subjected to compositional studies.

2022). However, research that includes microstructural studies as an essential part of the analytical protocol is being incorporated. This will be the case at Los Castillejos de Fuente Obejuna and Sierra Palacio I (Perez-L'Huillier, 2022) and the El Peñón de Penarroya-Pueblonuevo site (Alto Guadiato valley, Córdoba), where three metallographic studies are being carried out for chronologies that the authors attribute to *the* so-called *Chalcolithic period* (Perez-L'Huillier et al., 2025).

In a similar vein, we could discuss another publication that studies the state of copper mining and its association with settlement networks in the provinces of Jaén and Almería, as evidenced by mining operations such as Cerro Minado and Mina José Martín Palacios, for example, and the metallurgical deposits of Peñalosa (Baños de la Encina, Jaén), Santa Bárbara (Huércal-Overa, Almería), Las Pilas (Mojácar, Almería) and Almizaraque and Zájara (Cuevas de Almanzora, Almería) (Montero, Rovira, 2022; Murillo et al., 2020, 2025).

More recent and specific is the summary work on prehistoric metallurgy in the Antequera area (Rodríguez Vinceiro et al., 2018), which refers to numerous sites with a relatively small number of metal products, although only elemental and lead isotope analyses were carried out. The authors themselves highlight the site of El Silillo (Antequera), with a chronology of 2.580–2.110 (cal BC 2σ) and remains of metallurgical activity, but above all El Castillejo (Almogía), which they identify as the main reference point for the study of prehistoric metallurgy in Malaga. Its occupation sequence would run from 2.856 to 2.210 (cal BC 2σ) and, according to its authors, it is the only site in Malaga where all the phases of the metallurgical production process (minerals, slag, products, moulds, etc.) are recorded in the stratigraphy. The settlement of El Castillejo appears, in the current state of research, to be the most important metallurgical centre in the area, being the largest and most strategically located, with metallurgical production not exclusively for self-sufficiency but also for regional exchange. Although, once again, metallography is not included in the battery of analyses carried out (elemental composition and Pb isotope analysis), the potential for future research to construct a broader spatial and temporal framework is exceptional.

On another chronological level, other recent work continues the trend of analysing materials from *the Argaric period*, notably studies on metallurgical production and consumption, with contributions or references to metallographic studies, such as those from the sites of Peñalosa (Baños de la Encina, Jaén), Castellón Alto (Galera, Granada) and La Terrera del Reloj (Dehesas de Guadix, Granada) (Contreras and Moreno, 2015; Moreno and Contreras, 2015; Montero and Murillo Barroso, 2010; Murillo Barroso et al., 2014, 2015). In these and other subsequent works, although proposing different interpretative models, the characteristics of such an important activity as prehistoric mining and metallurgy in the easternmost region of the southern peninsula are reflected upon (Arboledas-Martínez and Alarcón-García, 2018; Escanilla et al., 2025; Moreno et al., 2017; Murillo et al., 2020, 2024, 2025).

Therefore, if we look at the archaeological sites documented with evidence of metallurgy dating back to the third millennium BC in the "southeast" of the Iberian Peninsula, we will notice how limited and partial their archaeometallurgical analyses are, especially when compared to those from the *Argaric* period (Lull et al., 2010). This is despite the proclaimed importance of metallurgical technology and metal in the south-east of the peninsula.

2.2. *The analysed set*

The study corpus consists of 30 copper-based products, selected to represent a functional and typological sample of the metallurgical production of these sites. The distribution is as follows (Σ 30): Marroquíes Bajos (n = 10), Las Eras del Alcázar (n = 10) and Castro del Río (n = 10). These products and metal remains were selected based on criteria of availability, functionality, typology and state of preservation, prioritising those from archaeological contexts in which the reliability of micro-spatial and contextual information could be guaranteed. Products with a high degree of oxidation that prevented a representative metallographic study were excluded (Fig. 10).

The analysed collection consists mainly of tools and weapons, representing morphotypes that are common in archaeological contexts on the Iberian Peninsula from the 4th-3rd and 2nd millennia BC (Bashore et al., 2014; Bayona, 2008; Lull et al., 2010). Typologically, the assemblage consists mainly of daggers and knives, as well as chisels, awls, needles and saw blades. Morphometrically, laminar elements (knives, daggers)[10] and longitudinal elements in bar/rod format (punches, needles) can be distinguished, allowing for a robust comparative analysis of production patterns (Table 1). This selection, which reinforces a powerful corpus for the study of prehistoric technology, is highly significant both quantitatively and qualitatively, as it completes the most comprehensive analytical systematisation available for the time frame in which these sites are located (Bayona, 2008, 2015).

A statistical approach, corroborated by the archaeological contexts of the selected samples, identifies the predominant presence of products for domestic use, such as tools for production and consumption tasks (Marroquíes Bajos: 60–70%, n = 6/7; Las Eras del Alcázar: 50%, n = 5; Castro del Río: 20–50%, n = 2/5). Alongside these, although in varying proportions, we identified the presence of weapons (Marroquíes Bajos: 30–40%, n = 3/4; Las Eras del Alcázar: 50%, n = 5; Castro del Río: 40–70%, n = 4/7).

2.3. *Analytical methodology*

The archaeometric analysis protocol and methodological framework applied in this research have been designed to accurately define the technological processes involved in the manufacture of copper-based products. Archaeometallurgy, as a historical discipline, is understood to have as its fundamental objective the recognition of the level of development necessary for the manufacture of metal products (Bayona, 2008, 2015, 2018; Gutiérrez et al., 2011; Killick, Fenn, 2012; Pearce, 2016; Roberts, Thornton, 2014; Wayman, 2000). This approach, which brings together specialists from the experimental and social sciences, must go beyond the mere description of materials, encouraging the incorporation of new elements and procedures into the discipline of archaeology (Dolfini, Crellin, 2016; Güder et al., 2018; Hüls et al., 2023; Martinón-Torres, 2002). This study has therefore applied a systematic methodology based on traceological analysis, textural and compositional characterisation, and the study of the internal structure and mechanical properties of the samples. The detailed protocol can be found in Bayona (2018).

2.3.1. *Sample preparation*

The preparation of samples for microscopic analysis is a critical phase that requires a rigorous extraction and treatment method to obtain mirror-like polishes. Millimetre-sized fragments were extracted from each sample by micro-cutting with a STRUERS MINITOM precision cutter, using a diamond-coated CBN disc to avoid plastic deformation. The samples were embedded in moulds with MECAPREX resin, a cold mounting method that prevents thermal alterations. Subsequently, a flat grinding process (DISCOPLAN TS) and fine grinding with silicon carbide (SiC) abrasive was carried out on a STRUERS KNUTH-ROTOR-3 grinding machine, with intermediate immersions in an ULTRASONS p ultrasonic bath to remove residues. The final polishing stage was carried out on a STRUERS DAP-6 polisher with cloths and alumina and diamond abrasives down to 0.1 μm to ensure an optimal surface. This sample preparation protocol, in cases of excessively soft material (≈ Cu) or in

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[10] The marked recurrence of laminar elements reflects the interest in specifically characterising their processing techniques in relation to the selective application of complex treatments in the manufacture of this type of product, evaluated in relation to other previously studied contexts (Bayona, 2008, 2013, 2015).

Fig. 10. Photograph and archaeological drawing of some of the samples selected for archaeological study from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río.

the presence of preparation defects due to particle drag (supergene alteration edges, inclusions, etc.), included manual polishing in a PRESI MECAPOL 2B (38 POISAT) polisher using a solid solution of magnesium oxide (MgO). Finally, the polished samples were coated with carbon using the *sputtering* technique in a BALTEC-SCD 005 metalliser

2.3.2. *Compositional analysis*

An electron probe microanalyser (EPMA) was used to analyse the elemental chemical composition of the metal matrix, inclusions, exolutions and alterations in the samples. This equipment offers a detection limit and analysis quality superior to those of a conventional scanning electron microscope (SEM). A JEOL JXA-8200 SuperProbe microprobe was used, equipped with four wavelength dispersion spectrometers (WDS) and an energy dispersion spectrometer (EDS). The standard working conditions were set at 20 kv acceleration voltage, 20^{-9} A probe current and a beam diameter of 5–10 μm. The quantification of elemental concentrations was carried out using certified international reference standards (*Micro-Analysis Consultants Limited)*.

2.3.3. *Microstructural analysis*

Metallographic observation was carried out using a NIKON ECLIPSE LV 100 POL optical microscope with 10-500x lenses. This equipment allows the identification of the crystalline structure, grain size and the presence of diagnostic phases of the manufacturing processes. To complement the analysis, a NIKON EPIPHOT inverted metallographic microscope (100-1000x) was used. The images were captured using digital acquisition equipment (NIKON DIGITAL SIGHT DS-Fi1), allowing for detailed recording and exhaustive analysis of the thermal and mechanical history of each sample (Calvo, 1972; Gil, Manero, 2005; Scott, 1991). For the Cu-based samples, the immersion technique was used, mainly in ferric chloride ($FeCl_3$) and hydrochloric acid in aqueous solution (HCl) and/or ammonium persulphate and ammonia in aqueous solution ($(NH_4)_2S_2O_8$). This metallographic study method followed the ASTM E 407 standard for micro-etching.[11]

2.3.4. *Analysis of mechanical properties*

The evaluation of the mechanical properties of the samples focused on determining their hardness. Microhardness tests were performed using the Vickers method, in accordance with the guidelines of ASTM E 92–82,[12] on a SHIMADZU MICRO HARDNESS TESTER HMV-G21D automatic microhardness tester. The Vickers method allows hardness to be determined on a smaller scale and even the hardness of individual

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[11] *Standard Practice for Microetching Metals and Alloys* of the *American Society for Testing and Materials.* See also Petzow, 1978.

[12] *Standard Test Method for Vickers Hardness of Metallic Materials from the American Society for Testing and Materials.*

Table 1
Morphometric data of the metal products selected from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río. Maximum measurements.

Reg. Nº	Type	Length	Width	Thickness	Weigth
MB-1002	Knife	12,27	3,01	0,25	28,25
MB-1022-2	Dagger rivet	2,22	0,57	0,38	1,05
MB-1198	Dagger	12,8	2,21	0,31	21,07
MB-1200	Saw sheet	4,41	2,15	0,21	5,44
MB-5000	Arrohead?	3,11	1,11	0,55	5,25
STJ-193	Chisel	5,68	0,46	0,38	5,72
STJ-481	Chisel	5,04	0,49	0,44	5,05
STJ-1632	Chisel	5,59	0,59	0,61	11,61
STJ-1636	Chisel?	11,45	0,46	0,37	7,99
STJ-3783	Wire	4,25	0,21	0,22	5,15

Reg. Nº	Type	Length	Width	Thickness	Weigth
UB-2104-T1	Dagger	5,22	3,2	0,27	16,5
UB-2571	Awl	5,71	0,32	0,31	3,12
UB-2572-1	Awl	4,12	0,23	0,21	1,27
UB-2635	Awl	6,58	0,29	0,25	2,78
UB-2958	Needle	4,51	0,31	0,28	1,55
UB-2988	Dagger	7,01	2,31	0,32	18,1
UB-4404	Needle	5,49	0,28	0,25	1,46
UB-6000	Dagger	7,68	3,61	0,35	27,87
UB-13003-T13	Dagger	15,33	2,41	0,21	19,08
UB-14151	Dagger	8,32	1,81	0,24	7,57

Reg. Nº	Type	Length	Width	Thickness	Weigth
CR-01	Undetermined	3,47	2,28	0,39	10,22
CR-02	Dagger	4,71	2,55	0,19	10,11
CR-03	Saw sheet	7,23	1,68	0,26	7,87
CR-04	Dagger	6,48	1,74	0,21	6,3
CR-05	Dagger	6,86	3,05	0,28	18,73
CR-06	Arrohead	5,46	1,67	0,38	6,27
CR-07	Knife	6,81	2,24	0,25	7,44
CR-08	Dagger	6,61	2,01	0,36	15,91
CR-09	Saw sheet	8,18	3,22	0,34	28,86
CR-10	Knife	5,68	1,84	0,31	9,62

phases in a multiphase material to be determined. In each test, a diamond pyramid indenter with an angle of 136° presses the surface of the sample with a preset/variable load (200–300 gf) for 15 s. The Vickers hardness (H_V) is calculated from the average of the diagonals of the resulting indentation (HV = P/A),[13] providing an accurate measure of the material's resistance to plastic deformation. The minimum number of measurements is based on the performance of a cross-axis test in order to measure the difference in microhardness between the edges and the centre of each sample. In this work, due to the particularities of the sampling, the *nm* of valid measurements was 4. The maximum number of measurements is established according to the dimensions and nature of each sample. In this work, the *nmx* of measurements was 15.

3. Results: A uniform technological spectrum

The archaeometric analyses of the metal samples from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río included the study of the elemental chemical composition, the determination of phases and inclusions, the microstructural analysis and the evaluation of their mechanical qualities. The data obtained from 358 specific analyses via EPMA, 287 microhardness measurements and 30 metallographic studies allows for a robust interpretation of the technological processes applied in their production. The results are presented below based on their main compositional and microstructural variables, followed by an interrelated assessment within the framework of the interpretation of technological models of prehistoric metallurgy.

3.1. Compositional profile: Arsenic copper ranges

Quantitative analyses carried out via EPMA have defined binary copper (Cu)-based alloys with dissimilar arsenic (As) contents (Supplementary data). According to the most common classification of copper and its alloys, we would be looking at the *dilute-copper* or *high-copper alloys* family. Alongside these, a sample has also been defined where the solute in the solid solution is tin (Sn). The overall composition of a metal alloy can be considered an important tracer variable in the study of metallurgical activity from approaches related to production control and the properties of the final product (Bayona, 2008, 2015, 2018). In Marroquíes Bajos, the arsenic content ranges from 1.1 to 6.48% As (average 2.78% As), while in Las Eras del Alcázar the range is more homogeneous and significantly higher (0.5–6.42% As; average 3.24% As). The Castro del Río site shows a lower average (1.78% As). The only bronze artefact (CR-01, with 11.76–22.36% Sn) is interpreted as an intentional alloy, and its presence suggests wider supply/exchange networks linked to the exploitation/circulation of tin and chronologies at the upper limits of the established range (Fig. 11).

The percentages and trends in the samples from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río could be compatible with sources of raw materials characterised by high As contents. This is consistent with the proposal on the distribution of arsenic contents as a result of the natural variability of copper-bearing minerals in the south-east of the Iberian Peninsula (Rovira, 2004, 2016). However, this proposal is contradicted by research showing that *the distribution of arsenic in the southeast is neither random nor widespread among natural copper resources but occurs in very specific areas affected by neogenic epigenetic processes (*Escanilla et al., 2016).

The analysis of major elements in the Cu base samples has been completed with the characterisation and identification of minor elements, traces, inclusions and phases that make up the metal alloys. The traces and impurities in the metal matrix of the samples analysed characterise metals that, in most cases, come from the reduction of minerals that can be considered chemically and texturally complex.

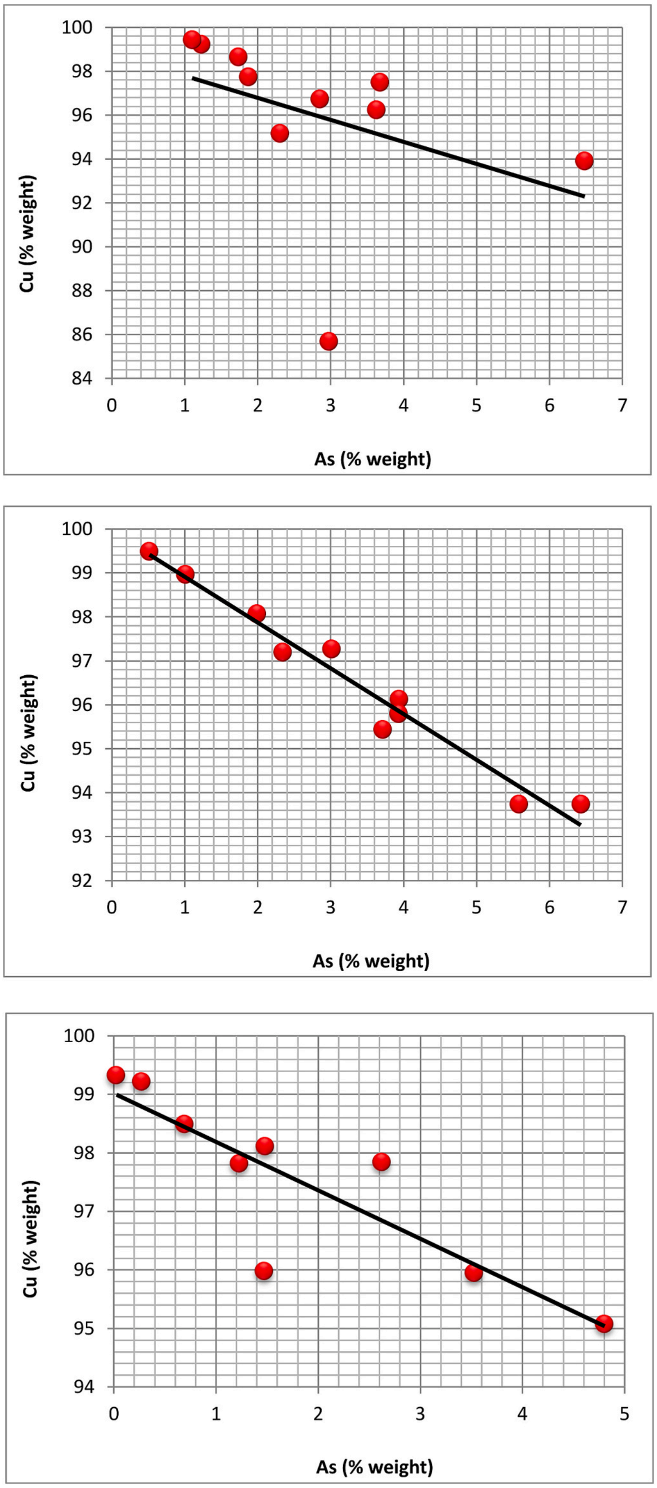

Fig. 11. Cu/As content ratio (% by weight): Top) Marroquíes Bajos (n = 10), Middle) Las Eras del Alcázar (n = 10), Bottom) Castro del Río (n = 9). Representation of the weighted averages per sample of quantitative acquisitions via EPMA.

Although the trace element and impurities, the samples were not statistically discriminatory, some significant relationships and presences were defined that may indicate compatibility with polymetallic mineralisation with impurities of Ag, Pb, Bi or tungsten. In some cases, their restricted distribution range could be directly related to specific geological contexts in the south of the peninsula.

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[13] Where *HV* = *Vickers* hardness rating, P = applied load, and A = indentation area.

3.2. *Microstructural profile: Complex chaînes opératoires*[14]

Based on the copper-arsenic equilibrium diagram, the samples analysed belong to the range of single-phase alloys in solid solution with alpha phase structures where the high arsenic concentration in certain samples led to the formation of eutectic phases (γ) that macroscopically resolve as pseudomonophasic. Based on the Cu–O equilibrium diagram and the reduced solubility of oxygen in the copper matrix –Cu-Cu_2O ratio- have also identified these eutectic phases and formations of the Cu_2O compound (Merino, 2012; Pereira et al., 2013; Schramm et al., 2005).

The metallographic study of the samples has made it possible to identify two different manufacturing techniques that define the production of metal products in the contexts analysed within the selected space–time framework (Fig. 12).[15] The overall microstructure of the population analysed reveals a history of thermal and mechanical treatments that directly contradicts the idea of a simple technology of majority use.[16] In this regard, the total absence (0% of the 29 samples analysed) of simple manufacturing sequences (casting followed by forging,[17] C + H) is very significant. The different ranges of tension, thickness reduction and grain sizes point both to a combination of thermal and mechanical treatments and to the existence of work cycles, which we have already defined in other publications (Bayona, 2015, 2018).[18]

Instead, the entire set is classified into two complex *operational chains*:

- C + H + A (Smelting → Forging → Final Annealing): This sequence, which involves a forging process followed by a final heat treatment, was identified in 28% (n = 8) of the products studied.
- C + H + A + FH (Smelting → Forging → Intermediate Annealing → Final Forging): This more elaborate sequence, which incorporates a final forging phase after thermal annealing, represents the dominant technological option, identified in 72% (n = 21) of the analysed set.

The sequence of forging after casting in moulds followed by a thermal process as the final phase (C + H + A) would consist of 20% of the samples from Marroquíes Bajos, 40% of the samples from Las Eras del Alcázar and 22% of those from Castro del Río. The sequence (C + H + A + FH), which incorporates a final forging phase after annealing/recrystallisation,[19] would consist of 80%, 60% and 78% respectively of the samples analysed (Fig. 13).

It is highly significant that, in a broad sample such as the one analysed, from three different archaeological contexts, no simple operational chains consisting of the exclusive application of forging treatments after casting (C + H) have been documented. In this regard, and although the issue of copper ductility is extremely complex, given that in all the cases analysed in the samples from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río there has been a combination – and alternation – of thermo-mechanical treatments, the generalised proposal of *a single step* cannot be upheld.

The statistical association (*Pearson Correlation Coefficient*) of the variables product type and production technique (Table 2) reinforces the probability of intentional production control, as the statistical correlations are close to positive in two cases and very consistent in another. Thus, in Lower Moroccans (0.78), the uniformity of the group of laminar products (knives, daggers, saw blades and arrowheads) stands out, all of which have been manufactured using a complex process (C + H + A + FH),[20] with the statistical consistency determined by the homogeneity of the chisel group (40% of the sample). In Las Eras del Alcázar (0.46), the uniformity of the manufacturing techniques of the group of punches and needles is noteworthy, as well as the relative trend in the case of daggers. With regard to Castro del Río (0.42), the high

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[14] The notion of *chaîne opératoire,* derived from technological anthropology, refers to the series of technical operations and decisions that transform a raw material into a final object, including use, recycling and disposal. Its application to metallurgy makes it possible to identify production patterns and understand how communities controlled the necessary technological variables.

[15] From left to right and top to bottom: **1)** Microstructure of C+H+A+FH with remnants of the original dendritic structure and the presence of abundant *Neumann lines* crossed with twinned grains deformation. The grain size (G=2–4), banding and chaotic arrangement of the crystals indicate the high intensity of the mechanical processes applied to this dagger. Hv indentation. **2)** Formation of swarms of Cu sulphate Cu ($CuSO_4$) oxides with a globular morphology in cavities and areas of alteration of the metal mass of this dagger. EPMA image. **3)** Complex C+H+A+FH treatment on this arrowhead with evidence of moderate final forging. Metal flow and traces of nucleation in bands can be observed. **4)** Knife with fibrous-laminar crystalline morphology (blade and sheath). The micrograph (200x) reveals a structure with *slip lines* showing intense plastic deformation (C+H+A+FH↑). Hv indentation. **5)** This sample (dagger) has a high concentration of As and strongly arsenic-rich microdomains, with concentrations close to 30% As (gamma phase with Cu_3As composition), whose arrangement thickening the grain boundaries defines the underlying crystalline structure. EPMA image. **6)** Chisel with FCC (*Face Centred Cubic)* texture subjected to sequences of mechanical deformation and thermal cycles (C+H+A+FH). The irregular arrangement, deformed twins, slip bands due to post-casting operations and curvilinear grain boundaries indicate the forcefulness and repetition of the forging work. The annealed twins show dimensions between 25–150 μm. The cross-banded reticulation is due to the change in position of the object during hammering and, therefore, to the deforming stress. The residual nuclear structure in compressed planes is the result of incomplete homogenisation processes (≤600-700 °C). Hv indentations. **7)** This dagger is characterised by very intense forging, with thickness reduction levels of up to 80%. The microstructure appears chaotic with a massive presence of *Neumann lines,* where the grain boundaries are obliterated and the effect of metal flow and deformation and curvature of the grain boundaries and their twins can be seen (100x). The size of the newly formed grains (G index ≤5) and their severe dislocation indicate inefficient heat treatment. The resulting hardness is extremely high (up to 193.4 Hv). **8)** This punch shows filiform arsenic segregates or exolutions corresponding to immiscible melts with contents of up to 27% As, located at the grain boundaries, on the surface of the sample (reverse segregation) or cutting through the matrix (intergranular As-rich phase). The presence of inclusions with significant contents of Bi, Bi+As and cuprite (Cu_2O) is identified. Oxidation processes define copper oxides and arsenates. Some inclusions in the alteration zone correspond to stoichiometries typical of juanitaite ($(Bi(Cu,Ca,Fe)_{10}(AsO_4)_4(OH)_{11}\cdot 2H_2O)$). EPMA image. **9)** Metallography of this dagger with a fractured tip reveals an overall lattice of polygonal (non-idiomorphic) twin crystals where the twins are visible as straight lines (25–50 μm) but not the grain boundaries, suggesting insufficient annealing and recrystallisation (normalisation?). The subtle *slip lines* could indicate a slight (↓) forging after annealing (C+H+A+FH?).

[16] We must point out that the necessary selection of micrographs may prevent some of the aspects referred to in the text from being recognised, although at this point we have endeavoured to make a graphic selection of each and every one of the different aspects described.

[17] The question of forging, whether cold or hot, is not an aspect to be developed in this work, although our position differs from traditional models of interpretation. See Budd, 1991.

[18] The phenomena of embrittlement and fragility are proportional to the deformation suffered. It should be noted that the percentage of reduction that a material can undergo without risk of breakage varies with a number of factors such as chemical composition, grain size, type of stress and tension, etc. Some authors place this inflection point at reductions of around 40–50% (Pifferetti, 2012).

[19] Thermal annealing restores the ductility and malleability of metals, modifying their mechanical properties. Recrystallisation treatments allow additional percentages of deformation without severe fracture processes.

[20] For similar results in the south-western peninsular region, see Bayona (2008, 2015).

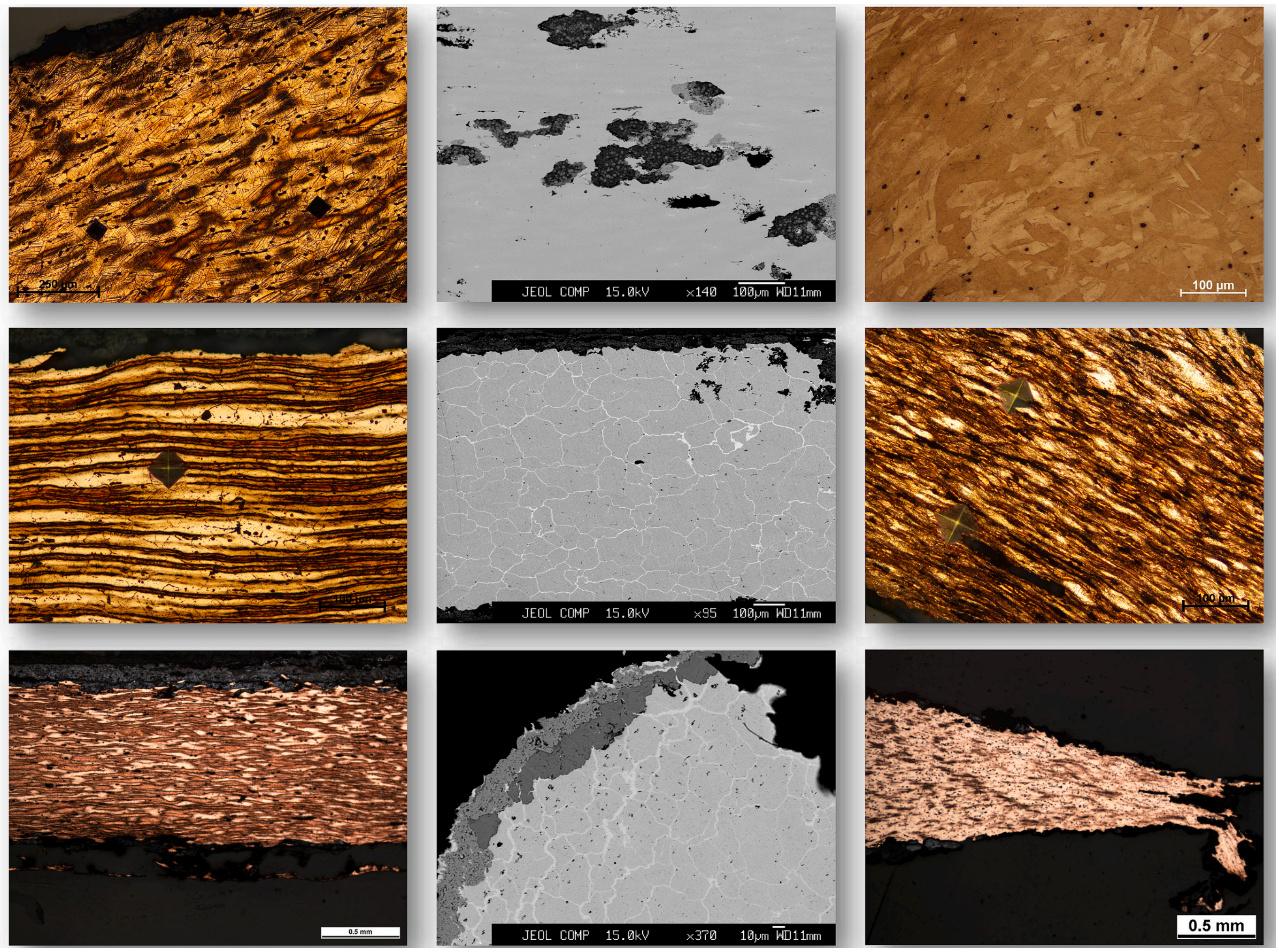

Fig. 12. Selection of representative micrographs of the complex manufacturing sequences identified at the three sites.

homogeneity of the group of laminar preforms is noteworthy, particularly in the case of knives.[21]

3.3. *Microhardness profiles: Statistical trend towards intentionality*

The results of the 287 Vickers microhardness tests (H_V) carried out on the entire sample reinforce the microstructural interpretations and reveal a positive statistical relationship with regard to the manipulation of the mechanical properties of the products. Of the series of measurements carried out on the sample analysed in order to establish its microstructural hardness and mechanical penetration resistance qualities, 114 correspond to Marroquíes Bajos, 81 to Las Eras del Alcázar and 92 to Castro del Río. The homogeneity of the values was calculated based on the *standard deviation* and *coefficient of variation* of each sample (Table 3).

Although it is very difficult to establish theoretical hypotheses about the hardness of a material based solely on the production technique or the As content (Bayona, 2008, 2015, 2018; Budd and Ottaway, 1995; Pereira et al., 2015; Valério et al., 2014, 2016), there is evidence of intentional manipulation of the properties of metals and a clear general trend towards progressive hardening towards the most functional areas (cutting edges and tips). The conical or parabolic distribution of hardness (Fig. 14), with the highest values on the *cutting edges* and *borders*, is a direct consequence of the greater intensity and frequency of the thermo-mechanical processes experienced in these areas during manufacture (Bayona, 2008, 2018; Wang and Ottaway, 2004). As an example, the UB-14151 dagger from Las Eras del Alcázar has values of up to 193.4 H_V on its cutting edge, in contrast to areas of the core that do not exceed 118.3 H_V, evidencing intense differential handling.

The *Pearson* statistical correlation test carried out between the microhardness value matrices and the arsenic content shows the existence of correlation indices defined as weak for Marroquíes Bajos (0.37) and Las Eras del Alcázar (0.38) and non-existent for Castro del Río (0.08). The behaviour of the Castro del Río samples is anomalous, given that the correspondence between the As and H_V indices does not follow proportional relationships, and where the values and their variation give rise to contradictory expressions (0.27% As → 122.4 H_V / 4.8% As → 104.5 H_V).

Although the correlation test values and the reliability of the trend line (R^2 value) do not indicate the absence of a positive relationship in several of the series analysed, we must accept that the As rates of an alloy and their direct and proportional influence on their H_V microhardness ranges only partially meet the defined theoretical criteria (American Society for Metals Handbook, 1998; Budd and Ottaway, 1995; Northover, 1989; Pereira et al., 2013), where the purity of copper

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[21] This positive correlation should be assessed with some caution, as the absolute sizes of some of the defined groups are statistically insignificant and the implementation of forging and annealing cycles would group the entire sample into a single set.

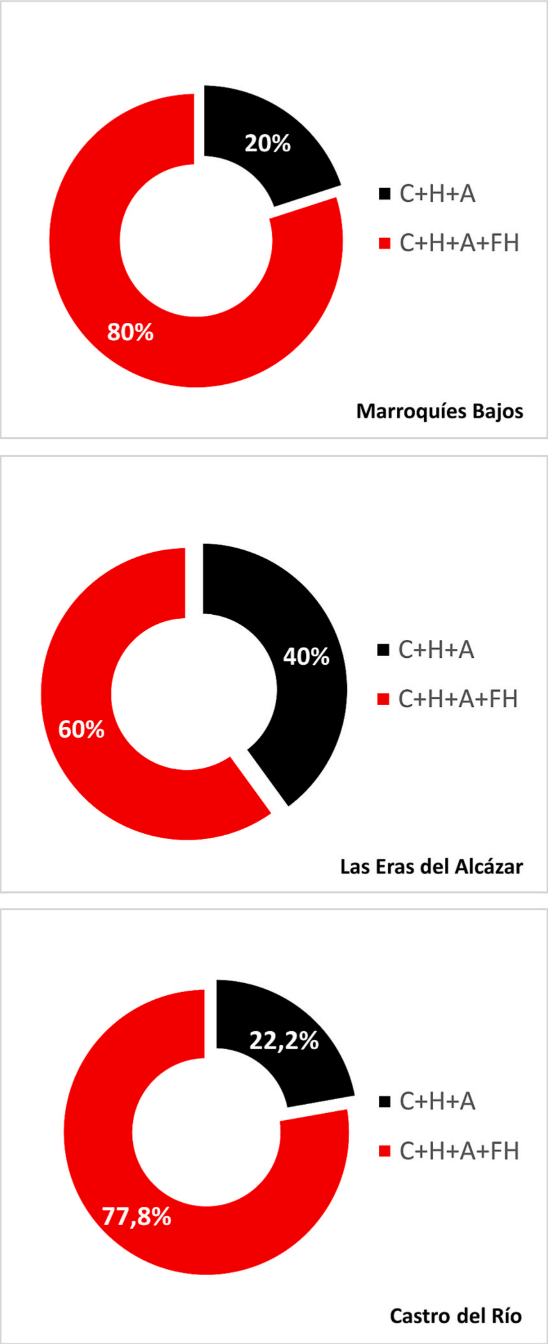

Fig. 13. Distribution of production techniques in the metal samples analysed from Marroquíes Bajos (n = 10), Las Eras del Alcázar (n = 10) and Castro del Río (n = 10).

(presence/absence of arsenic content) is directly related to its hardness (Fig. 15).

With regard to the comparison between microhardness values and defined morphotypes (*Pearson Correlation Coefficient*), for the samples from Marroquíes Bajos, the statistical correlation value could not be calculated due to the lack of a minimum number of necessary groups. In the case of the Las Eras del Alcázar samples, the statistical correlation value shows a negative and non-existent relationship (−0.21). The oscillation of the values ($\geq 89.6 - \leq 141.7\ H_V$) calculated for the largest group (daggers) explains the absence of correlation, which is much more evident, although with a smaller population (n = 3), in the case of awls

Table 2
Production techniques applied in the manufacture of metal products from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río.

Reg. N°	Type	*Chaîne opératoire*
MB-1022–2	Dagger rivet	C + H + A
STJ-3783	Wire	C + H + A
MB-1002	Knife	C + H + A + FH
MB-1198	Dagger	C + H + A + FH
MB-1200	Saw sheet	C + H + A + FH
MB-5000	Arrowhead?	C + H + A + FH
STJ-193	Chisel	C + H + A + FH
STJ-481	Chisel	C + H + A + FH
STJ-1632	Chisel	C + H + A + FH
STJ-1636	Chisel?	C + H + A + FH
Reg. N°	Type	*Chaîne opératoire*
UB-2571	Awl	C + H + A
UB-2572–1	Awl	C + H + A
UB-2988	Dagger	C + H + A
UB-6000	Dagger	C + H + A
UB-2104-T1	Dagger	C + H + A + FH
UB-2635	Awl	C + H + A + FH
UB-2958	Needle	C + H + A + FH
UB-4404	Needle	C + H + A + FH
UB-13003-T13	Dagger	C + H + A + FH
UB-14151	Dagger	C + H + A + FH
Reg. N°	Type	*Chaîne opératoire*
CR-05	Dagger	C + H + A
CR-09	Saw sheet	C + H + A
CR-02	Dagger	C + H + A + FH
CR-03	Saw sheet	C + H + A + FH
CR-04	Dagger	C + H + A + FH
CR-06	Arrowhead	C + H + A + FH
CR-07	Knife	C + H + A + FH
CR-08	Dagger	C + H + A + FH
CR-10	Knife	C + H + A + FH
CR-01	Undetermined	Not available

($\geq 50.8 - \leq 161.2\ H_V$). With regard to the Castro del Río sample, we can report a positive relationship between microhardness and laminar preforms, since the application of more forceful mechanical treatments (theoretically) is reflected in the homogeneous allocation of microhardnesses in this group, in an approximate range of ($\geq 100 - \leq 115$ HV). However, it should be noted that the calculated statistical correlation (0.52) has been influenced by the disparity in values within the knife group, justified by the significant presence of altered copper metal compounds in one of the specimens. The homogeneity of microhardness values in the group of saw blades (laminar) has had a positive influence on the test result.

For the sampling from Las Eras del Alcázar, with longer and more homogeneous series, the correlation coefficient is statistically classified as good (0.80), where all the highest microhardness values of the samples are associated with complex production techniques finished with forging treatments (C + H + A + FH). In these cases, despite the combination of cycles, it has been tested how structural hardness levels decrease –in the entire population analysed-with the final application of heat treatments (A) (Fig. 16).

4. Discussion

4.1. *A technological syntax of shared production*

The data from the archaeometric study of Marroquíes Bajos, Las Eras del Alcázar and Castro del Río, by enabling direct comparison with the models defined for the southwestern area (Bayona, 2008, 2015), allow for a reliable and indisputable conclusion: the technological tradition for the manufacture of copper-based products in the third millennium BC is, based on the available corpus, significantly homogeneous throughout the south of the Iberian Peninsula. The systematic and dominant use of complex and multiphase thermomechanical processes (cycles) is not a

Table 3
Vickers microhardness test performed on the metal samples analysed from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río.

Reg. N°	Type	Measurements	Hv Min.	Hv Max.	Average	Estand. Dev.	Coeff. Var. (%)
MB-1002	Knife (blade)	15	120.3	145.6	131	7	5.42
MB-1002	Knife (handle)	11	98.1	140.4	126	12	9.56
MB-1022-2	Dagger rivet	6	97.6	142.9	127	17	13.6
MB-1198	Dagger (blade)	15	109.3	189.3	152	25	16.4
MB-1198	Dagger (handle)	11	140.6	192.1	163	16	9.6
MB-1200	Saw sheet	13	94.4	139.9	127	13	10.4
MB-5000	Arrowhead?	7	128.4	143.8	136	6	14.64
STJ-193	Chisel	7	100.6	155.5	124	21	16.5
STJ-481	Chisel	10	44.1	60.4	52	6	11.88
STJ-1632	Chisel	9	115.4	166.4	149	16	11.1
STJ-1636	Chisel?	6	164.2	191.3	177	10	5.42
STJ-3783	Wire	4	50.9	156.9	90	47	51.88
TOTAL	12	114					
Reg. N°	Type	Measurements	Hv Min.	Hv Max.	Average	Estand. Dev.	Coeff. Var. (%)
UB-2104-T1	Dagger	10	114.8	210.9	142	36	25.3
UB-2571	Awl	6	45.1	57.5	51	4	8.6
UB-2572-1	Awl	6	68.9	120.6	97	17	17.1
UB-2635	Awl	5	153.1	177.3	161	10	6.09
UB-2958	Needle	6	114.2	127.7	120	5	4.4
UB-2988	Dagger	13	96.6	129.9	111	11	9.6
UB-4404	Needle	5	160.1	205.6	187	17	9.3
UB-6000	Dagger	9	73.9	109.3	90	12	14
UB-13003-T13	Dagger	9	98.1	168.6	131	23	17.2
UB-14151	Dagger	12	118.3	193.4	141	20	14.05
TOTAL	10	81					
Reg. N°	Type	Measurements	Hv Min.	Hv Max.	Average	Estand. Dev.	Coeff. Var. (%)
CR-01	Undetermined	nd					
CR-02	Dagger	11	94.9	132.6	116	10	8.9
CR-03	Saw sheet	11	91.2	132.6	111	12	11.08
CR-04	Dagger	8	90.4	128.1	104	13	12.3
CR-05	Dagger	10	78.4	110.9	99	11	10.9
CR-06	Arrowhead	6	116.1	128.1	122	5	3.8
CR-07	Knife	8	58.9	69.1	66	3	4.6
CR-08	Dagger	14	83.9	147	111	19	17.1
CR-09	Saw sheet	15	95.6	111.2	101	5	5.02
CR-10	Knife	9	97.1	129.9	109	11	10.3
TOTAL	10	92					

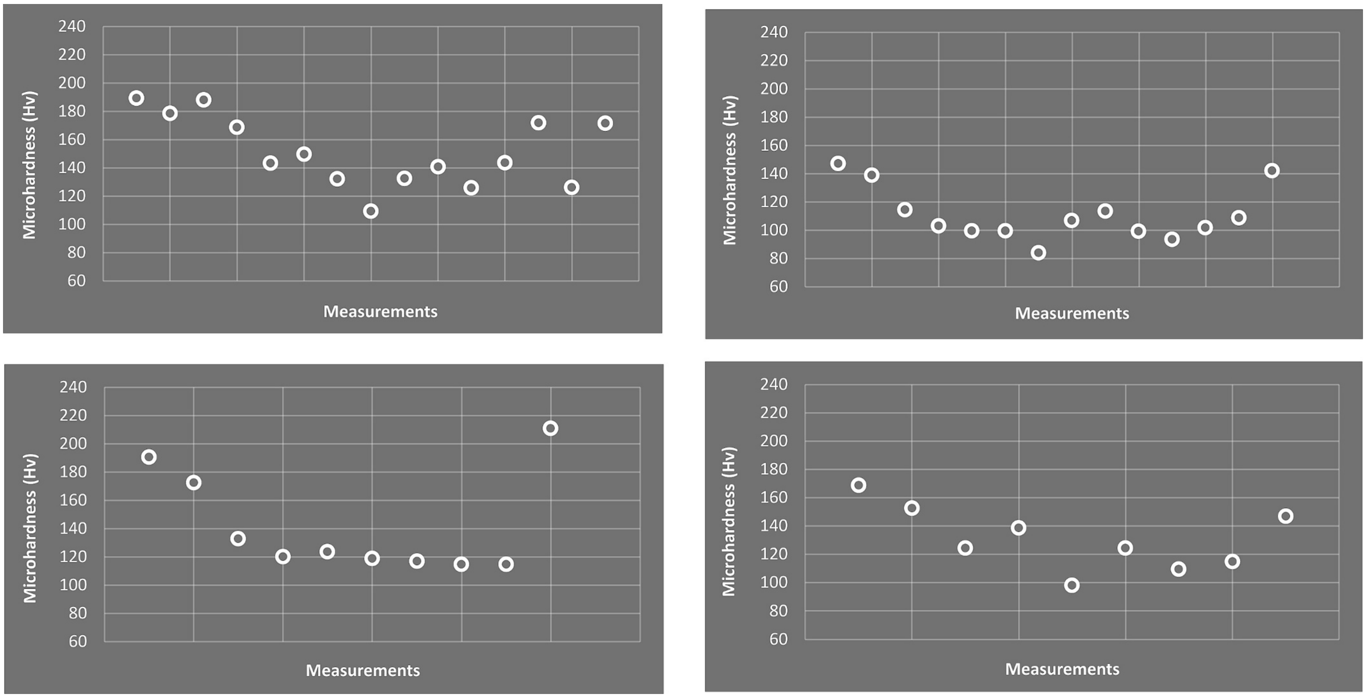

Fig. 14. Microhardness measurements on the longitudinal profile of a selection of laminar products (knives and daggers) from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río.

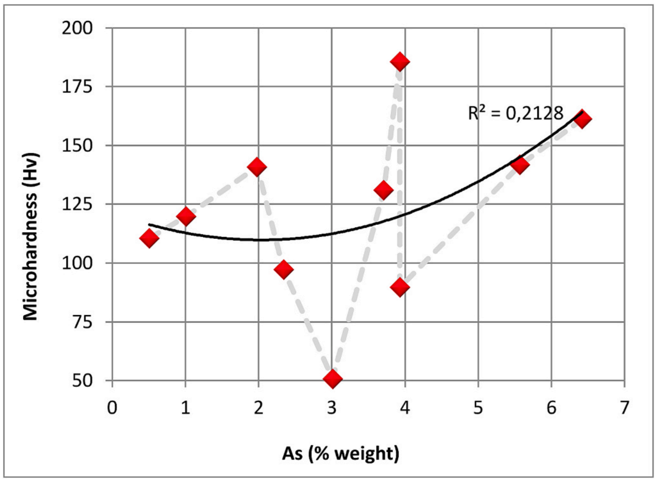

Fig. 15. Example of the relationship between As values (% by weight) and *Vickers* microhardness in metal products from Las Eras del Alcázar.

regional marker exclusive to the southwest, as was initially suggested and reaffirmed (Rovira, 2016),[22] but rather seems to respond to a technological syntax shared between contemporary communities that are distant from each other (Table 4).

As we have discussed elsewhere (Bayona, 2015, 2018), it is extremely complex to establish cause-and-effect relationships without processing the absolute values of each variable involved in the metallurgical production process (heat treatment time, cooling rate, temperature, forging time and intensity, original As content, etc.). Therefore, this recurring conceptual error must be overcome and it must be understood that the production technique referred to for each sample indicates the final process or phase in which the product was left, but not the number of cycles or times that heat or mechanical treatments were applied, nor their intensity or efficiency.

However, it is still relevant that, in a broad sample such as the one analysed, no simple operational chains consisting of the exclusive application of forging treatments after casting (C + H) have been documented. In our opinion, this indicates an efficient knowledge of metallurgical techniques and technology.[23] This opinion is also shared by other authors who assert that the 'operational chains' of metallurgy are a relevant indicator for determining the technological level achieved by a society (Costin, 1991; Contreras, Moreno, 2015). Along with this, the idea is also reiterated that, for chronologies of the *Bronze Age*, the significant improvement in the physical and mechanical qualities of processed products would go hand in hand, among other factors, with the application of a technological process characterised by the C + H + A + FH technique (Bashore et al., 2014). And a classic that is still latent in much research suggests that the most complex *chaîne opératoire* was considered the most efficient application of *workshop techniques,* since the resulting product exhibits better performance and qualities, although they only consider it representative and relevant in chronologies of *the* so-called *Middle Bronze Age (*Murillo, Montero, 2012; Rovira and Gómez, 2003).

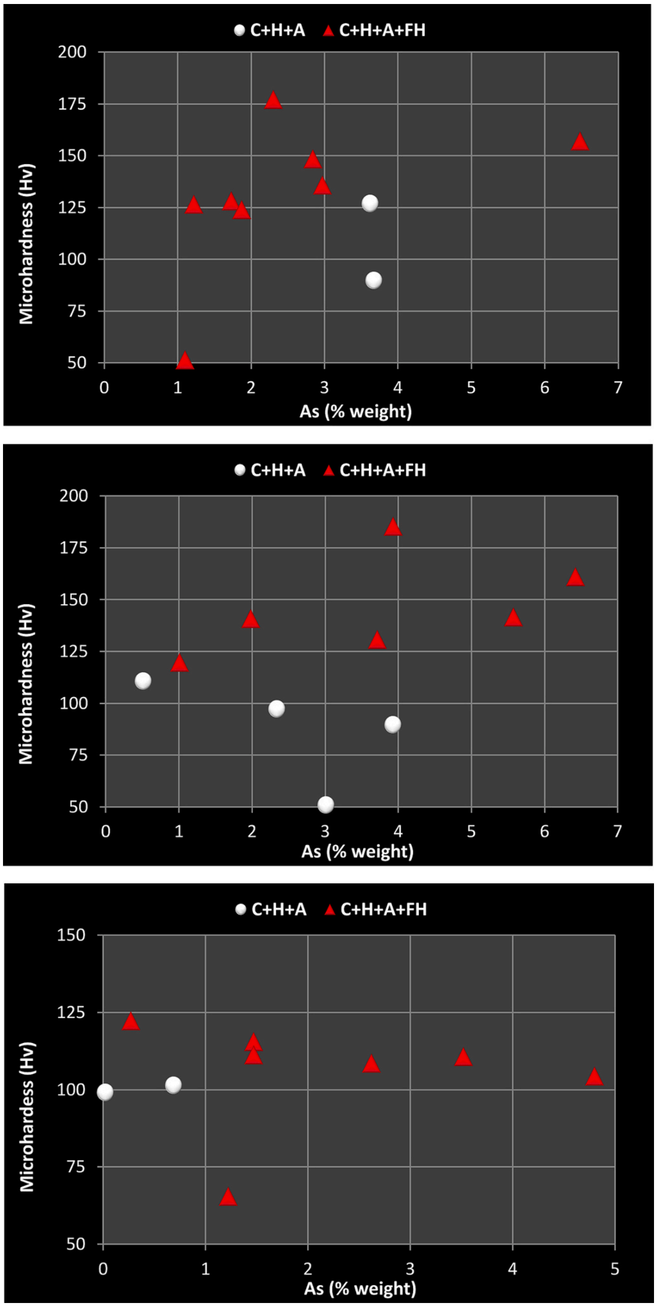

Fig. 16. Relationship between *Vickers* microhardness values, production technique and average As content (% by weight) of the samples analysed from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río.

However, the findings of our extensive archaeometric studies demonstrated (Bayona, 2008, 2015, 2018) and continue to demonstrate in this work that more complex manufacturing techniques were known and used repeatedly in the southern peninsula from the end of the 4th millennium and throughout the 3rd millennium BC. Therefore, not only can the predominance of exclusively mechanical treatments (C + H) no longer be sustained, but it must also be admitted that, in a representative statistical population, the values held until now have been reversed. This contrast is now confirmed in the very area where these traditional interpretations arose, which, at a metric and quantitative level, have been supersed by the increase in the number of cases analysed, in an indisputable position of statistical significance. This contrast is confirmed by metallographic studies at sites in the region (Perez-L'Huillier, 2022; Perez-L'Huillier et al., 2025), which predominantly document complex

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[22] Literal: …*Southwest, by providing new archaeometallurgical data of enormous importance that have contributed to generating new hypotheses that broaden the scope of the metallurgical model* (Rovira, 2016).

[23] Knowledge and control of metallurgical techniques is evident if we consider the high reductions in thickness shown by some of the samples analysed, which suggests the alternation of thermal and mechanical treatment cycles, as it has been found that forging treatments with severe reductions cause breakage and damage to metal products, estimating the need for several cycles of forging and annealing for thickness reductions of more than 50%, a percentage exceeded by all the laminar preforms studied.

Table 4
Analytical results and categories of the samples analysed from Marroquíes Bajos, Las Eras del Alcázar and Castro del Río: type of product, average As content (% by weight), average *Vickers* microhardness value and production technique.

Reg. N°	Type	As average (%)	Hv average	*Chaîne opératoire*
MB-1002	Knife	1.73	128	C+H+A+FH
MB-1022-2	Dagger rivet	3.62	127	C+H+A
MB-1198	Dagger	6.48	157	C+H+A+FH
MB-1200	Saw sheet	1.22	127	C+H+A+FH
MB-5000	Arrowhead?	2.97	136	C+H+A+FH
STJ-193	Chisel	1.87	124	C+H+A+FH
STJ-481	Chisel	1.10	52	C+H+A+FH
STJ-1632	Chisel	2.84	149	C+H+A+FH
STJ-1636	Chisel?	2.30	177	C+H+A+FH
STJ-3783	Wire	3.67	90	C+H+A
Reg. N°	Type	As average (%)	Hv average	*Chaîne opératoire*
UB-2104-T1	Dagger	5.57	142	C+H+A+FH
UB-2571	Awl	3.01	51	C+H+A
UB-2572-1	Awl	2.34	97	C+H+A
UB-2635	Awl	6.42	161	C+H+A+FH
UB-2958	Needle	1.01	120	C+H+A+FH
UB-2988	Dagger	0.51	111	C+H+A
UB-4404	Needle	3.93	187	C+H+A+FH
UB-6000	Dagger	3.93	90	C+H+A
UB-13003-T13	Dagger	3.71	131	C+H+A+FH
UB-14151	Dagger	1.98	141	C+H+A+FH
Reg. N°	Type	As average (%)	Hv average	*Chaîne opératoire*
CR-01	Undetermined	Not avail.	Not avail.	Not avail.
CR-02	Dagger	1.47	116	C+H+A+FH
CR-03	Saw sheet	1.47	111	C+H+A+FH
CR-04	Dagger	4.80	104	C+H+A+FH
CR-05	Dagger	0.02	99	C+H+A
CR-06	Arrowhead	0.27	122	C+H+A+FH
CR-07	Knife	1.22	66	C+H+A+FH
CR-08	Dagger	3.52	111	C+H+A+FH
CR-09	Saw sheet	0.69	101	C+H+A
CR-10	Knife	2.62	109	C+H+A+FH

or *long-chain* microstructures, meaning that the widespread use of simple treatments or the reduced application of heat treatments for the centre-southeast cannot continue to be the basic argument, although it has not been ruled out in recent studies (Valério et al., 2020).

Nevertheless, although the study of the theoretical relationships between the different variables (composition/operational chain/mechanical properties) of the sample analysed has shown both the existence of positive correlations and the absence of a significant statistical relationship, we must emphasise the relevance of the significantly positive trends and correlations detected in certain cases and in ranges of statistical strength, which we understand to be directed, from their conceptualisation, towards the search for and achievement of (productive) optimisation of results.

This reality, which opens the door to research and debate on the productive standardisation[24] in chronologies where it seemed to be prohibited, questions a model that had been unable to detect the strong presence and complexity of metallurgical activity in its initial phases, a model that was based on partial premises (Chapman, 1990, 2008; Molina and Cámara, 2005). A model, it must also be said, based on a much smaller analytical corpus but which was mistakenly taken as a general model. Refutation from falsifiability….

In this regard, it is important to define the limits of this statement. This study mainly details the final stages of an *operational chain* that appears to be the most common, although the validation of this technical/technological model does not exclude the existence of regional variability, with determining factors such as chronological analysis, mineral supply, the design of reduction-smelting furnaces and casting techniques, which require different analytical approaches and have not been addressed in this work. The complementary nature of this study will provide a less biased view of the metallurgical activity in prehistoric chronologies by promoting theoretical discussions based on empirical research, given that the contradictions expressed in the refutation debates are the main factor in scientific development. Validation from dialectics….

4.2. Re-evaluating specialisation in light of current debates

This defined technological homogeneity requires a re-evaluation of craft specialisation. While there are studies that highlight variability and independence in the scale of production (Montero, 2010; Montero et al., 2021; Molina et al., 2016; Montero and Murillo Barroso, 2016; Murillo et al., 2014, 2017, 2025; Valério et al., 2020, 2023), our data reveal an underlying technological syntax that unifies these diverse productive manifestations. The debate between domestic-scale metallurgy (in the southeast) and specialised metallurgy (in the southwest[25]) no longer makes sense or has any empirical basis. Radiocarbon chronologies of metallurgical contexts throughout the Guadalquivir basin identify the coexistence and contemporaneity of both copper production systems since the beginning of the third millennium, suggesting a much more complex reality (Nocete, 1989, 2001; Nocete et al., 2011). Approaches tending towards an empirically based explanation of a *metallurgy of optimisation* as opposed to a *metallurgy of sufficiency* lack scientific support, given that the technological variability defined by the coexistence of domestic and specialised production, the selective adoption of alloys and the articulation of extensive exchange networks point to a scenario in which communities adopted strategies adapted to their own historical contexts. This is what, for example, Las Eras del Alcázar shows, moving from a domestic production model (*Complete Household production*) to a different one (*Workshop at household level*) in its final phases of occupation. These were different models of organisation in which the most complex and efficient technological knowledge continued to be applied.[26]

Fortunately, the debates and discrepancies that the interpretation of metallurgical activity generates among researchers are increasingly being expressed in all their breadth. An example of this is the work on the metallurgical activity at Las Pilas (Mojácar, Almería) (Murillo et al., 2017), whose earliest evidence dates back to 2.905–2.743 cal BC, defined, although not unanimously by all authors, as small-scale metallurgy with limited specialisation and low efficiency.

And from these much-needed debates (thesis-antithesis), we cannot forget, although this is not the place to develop them, that the analysis of early copper metallurgy, its scale, intensity and technological profile, remains linked to the study of social complexity in archaeology and is taken as a barometer of the level of development of societies. And, given that there is no –…*metry* without –…*social,* it should be noted that data from our previous research programmes suggest that social verticalisation did not lie in a monopoly on technical knowledge and its resulting products, but in the ability to organise work, control access to raw materials and manage their asymmetrical distribution (Nocete, 2001, 2004). The existence of extensive exchange networks capable of moving

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[24] Small-scale standardisation or domestic production is an approach which, despite not being accepted by some researchers working on metallurgy in the Iberian Peninsula, develops the concept of efficiency adapted to the social and economic context (*Himalayan model*), not just metallurgical optimisation. See Pearce et al., 2022.

[25] Although initially not accepted by traditional archaeography, with its positivist and diffusionist overtones. See section 1.2. *A paradigm shift from the Southwest.*

[26] Variations in social organisation models and technical and spatial division of labour were also documented in the specialised mining and metallurgical settlement of Cabezo Juré, in the south-west of the peninsula (Nocete, 2004).

exotic materials and/or products (variscite, oolitic limestone, gold, copper, etc.), even if they did not constitute the dominant local production, would fall within the sphere of ostentation and the creation of symbols perpetuating social inequality. This cognitive process must also focus on the historical dimension of metallurgical technology(ies) and on the theoretical conception of metal *objects* as *social products* (Bayona, 2008; Nocete, 2001; Ruiz et al., 1986). Although this is another debate that has no place in this work, the theoretical-methodological debates of an epistemic nature that allow us to overcome the condition of a predominant and monolithic modelisation do have a place here.

This is also because empirical and analytical studies within our discipline would be meaningless without the implementation of a process that we have called *historical significance* (Bayona, 2008).

5. Conclusion: From knowledge of regional dichotomies to knowledge of shared knowledge

This research provides a model for refuting substantive theories based on data from the technological dichotomy that existed in the Iberian Peninsula during the third millennium BC.[27] Our main conclusion is that a complex, sophisticated and significantly homogeneous technological tradition (*technological continuum)*, characterised by the systematic use of complex thermo-mechanical treatments, seems to define the common material and immaterial heritage of craftsmen throughout this territory, according to the current state of research. In this sense, it is appropriate to introduce the so-called *third framework,* the psychophysical framework, which takes into account skill, cognition and the sensory dimension to construct perceptual categories, these being qualified as *a sensory update of the chaîne opératoire method* (Kuijpers, 2018).[28] Focusing on the qualities and characteristics of the material that are recognisable and relevant to artisans, and which can be perceived through the senses (texture, colour, brightness, hardness, behaviour of the metal, etc.) allows for a more complete analysis that combines technological and sensory aspects of artisanal production. This is undoubtedly a field that needs to be explored in depth and which may lie behind the homogenisation of production models at local, district and regional level.

However, this proposal for *a technological continuum* is not presented as universal, rigid or exclusive, since, for example, in the south-west we have documented both domestic and intensive and specialised production,[29] despite the fact that there is still a insistence on universalising the model of the data from each study or denying reliable analytical evidence for the south-east of the peninsula (Obón et al., 2020; Valério et al., 202030, 2023[30]). In other cases, there is a persistent tendency to present the production models of the south-west of the peninsula (traditional *vs.* alternative) as two opposing interpretations (Rovira et al. in Murillo et al., 2020). We argue that they are different manifestations of the same reality.[31]

In the analysis of prehistoric metallurgical activity, the explanation of local and regional processes must be considered an essential factor for the proper overall interpretation of the phenomena studied, since the historical reality is much more complex and is shaped by a diversity of models, based on their archaeological contexts, where metallurgical activity is represented both by specialised settlements or metallurgical districts and, of course, by domestic-scale production units (Bayona et al., 2012). A more far-reaching and significant historical exegesis is also shared by other researchers with regard to invalidating the dogma of *the immutable unicum* (Escanilla et al., 2016).

The qualitative leap forward represented by this study is underpinned by its innovative proposals, based on a programme of continuous, systematic and methodical analysis and a rigorous scientific research protocol. This analysis of metallurgical production in the central and south-eastern regions of the Iberian Peninsula has enabled us to move from knowledge of a specific reality to proposals for its explanation. The results have enabled the systematisation of studies on prehistoric metal technology in a broader context, suggesting a model of historical interpretation that is technologically based and distinct from and complementary to existing traditional models. And necessary. In this regard, it should be noted that some recent work in the same spatial and chronological framework has yielded similar results, at least in terms of the complex manufacturing technology of metal products and the existence of stable product circulation circuits on a supra-regional scale (Perez-L'Huillier, 2022; Perez-L'Huillier et al., 2025).

However, this is not incompatible or mutually exclusive, even if a model shift is required, as we must move away from viewing this vast region (southern peninsula) as the territory of a dichotomous model (simple *vs.* complex) and understand it as a mosaic of unequal technological centres and as a dynamic network of communities that shared a body of advanced metallurgical knowledge, without ignoring the need to expand the analytical populations and the geographical and temporal framework of comparative studies at the local and regional levels (Escanilla et al., 2025; La Duc et al., 2022; Pearce et al., 2022; Montero et al., 2021; Murillo Barroso et al., 2025; Rodríguez Vinceiro et al., 2018; Valério et al., 2020, 2023). This study has therefore not only increased the analytical population of the main metallographic corpora of the Iberian Peninsula (Bayona, 2008, 2015, 2018; Rovira and Montero, 2018), but also lays solid foundations for research into contemporary and later periods in the region to establish the diachronic limits and characteristics of such an important activity as prehistoric mining and metallurgy. However, this research continues to contrast domestic models, which are inefficient, decentralised and diverse, with intensive, organised and specialised metallurgical activity with social, economic and technological implications (Arboledas-Martínez and Alarcón-García, 2018; Moreno et al., 2017; Murillo et al., 2020, 2024; etc.). Neither simple nor complex. Simple and complex….

And, based on all this data, explore hypotheses about the presence/absence of technological models in the manufacture of metal products and participate in debates on technological skills and traditions, models and chronologies with a renewed and solid empirical basis (Bayona, 2008, 2015, 2018). We agree with Montero and Rovira (2022) when they state that there is still great potential for future archaeometallurgical research. Without in-depth and thorough archaeometric research programmes that seek to provide answers to our substantive theories, we will make little progress.

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[27] This, however, was once the *general models* of interpretation of domestic metallurgy, characterised by low productivity, simplicity, etc., had been overcome.

[28] The categories relating to manufacturing techniques, workshop processes, manufacturing, shaping, metalworking or the concept reminiscent of the systemic structuralism of french prehistoric ethnology most widely disseminated by *Chaines Opératoires or Operational Chains,* mainly address the indicators of metallurgical production technology in its most technical aspects. However, more generic conceptualisations that encompass all the variables of the process are also discussed (Banning, 2000). Recently, the *reconceptualisation* and revision of the term *Technical Operational Chain* (CTO) or *sequence of actions involved in the production of an artefact* has highlighted the complexity and relevance of this debate. See Martinón-Torres (2002) and Comendador Rey (2010).

[29] There are publications that identify and differentiate "metallurgical provinces" in the south-east and south-west of the peninsula. See Murillo et al., 2020.

[30] This publication states that: *annealing appears to be almost absent during the Chalcolithic in the southeastern region / It is worth noting that such development was not shared with other regions such as the southeastern Iberian Peninsula where the annealing operation is commonly absent until the MBA* (Rovira, Gómez, 2003).

[31] Translated: *Metallurgy is both what is done in blast furnaces and in rural smithies. The difference between the two lies in the complexity of the processes, the production tools used, the organisation of production and, probably, the quality of the product. However, both are realities that can perfectly coexist in the same space and time* (Bayona, 2008: p. 258).

This work, therefore, significantly reinforces the study of prehistoric copper metallurgical production technology in the Iberian Peninsula. It is a study from which to *construct* and fill in the gaps and lacunae that have unevenly affected different chronological periods and territorial areas. It is also a study from which to *deconstruct* "universal" theories and hypotheses about the technological features and ranges of metallurgical activity.

CRediT authorship contribution statement

Moisés R. Bayona: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Francisco Nocete Calvo:** Writing – original draft, Visualization, Supervision, Investigation, Funding acquisition, 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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Dedication

This article is dedicated to my mentor, Francisco Nocete Calvo (†2024).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2026.105645.

Data availability

Extended results are provided in Supplementary Data.

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